EFFECT OF PHOSPHORUS PLACEMENT IN REDUCED TILLAGE CROP PRODUCTION

by

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B.S., Oklahoma State University, 2002
M.S., Oklahoma State University, 2005

AN ABSTRACT OF A DISSERTATION

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Abstract

A number of questions are being raised concerning phosphorus (P) management as producers switch to minimum or no-tillage cropping systems. Benefits of P application are site specific and potential advantages need to be evaluated for each location. Deep band application effects on crop yield and soil P distribution have been studied, but conclusive results are lacking because of the complexity of environment and P placement interactions, particularly in moisture limited environments. Challenges in soil test sampling and interpretation have also affected P management in these reduced and no-tillage systems because of decreased confidence in soil test P data. The objectives of this research were to evaluate crop responses to P application rate and placement and to study the distribution of soil P concentration, both vertically and laterally at a number of locations in Kansas.

This research shows that crop growth at the sites evaluated was not negatively affected by P stratification, which was present at all sites at the beginning of the study. Phosphorus placement methods (broadcast and deep band) did not have significant effects on P responses. However, P application was required to achieve maximum yields at sites with low soil P, but high P sites did not consistently respond to P application. When P fertilizer was broadcast, shallow soil depths continued to have high soil test P, while deep band application increased soil P in the 7.6 to 15 cm depth. The addition of starter application with deep banding of P generally resulted in a more even vertical distribution of soil P. Soil test P data also demonstrated that the presence of bands can be confirmed through soil sampling, but the confidence of soil test P data in a vertical and lateral stratified soil was decreased. Soil samples taken from the band area had

highly variable P (high coefficient of variation) concentrations likely due to an inability to sample from within the P band or variability in P application. Soil sampling in these management systems proves to be challenging and will need further research to identify improved methods for soil test P sampling and interpretation.

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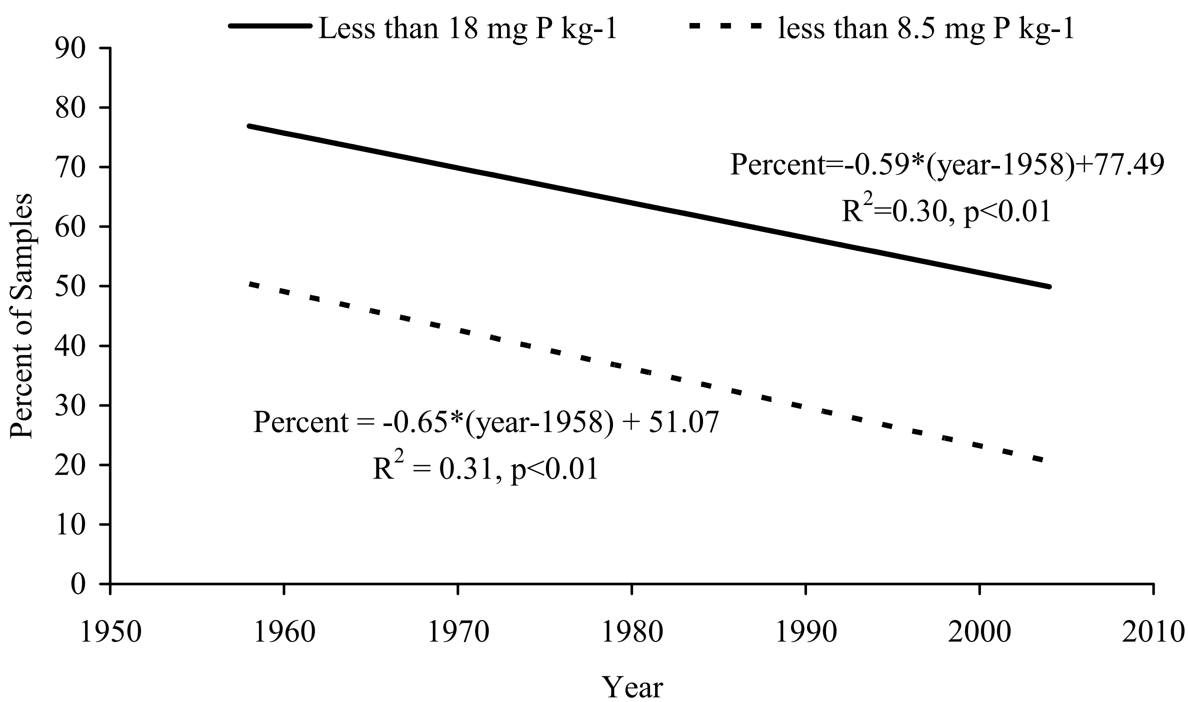
CHAPTER 1 - Phosphorus Placement in Reduced Tillage Crop Production

Introduction

Phosphorus (P) availability in soils is important as it commonly limits crop production (Halvorson and Black, 1985). Unpublished data from the KSU Soil Testing Laboratory (Figure 1.1) shows that while P soil test levels in Kansas are increasing, 50% of the samples from the eastern two-thirds of Kansas are currently below 18 mg kg^{-1}, or below 20 mg kg^{-1} (critical level) and 20% are below 8.5 mg kg^{-1} (severely deficient in available P).

Figure 1.1 Percent of samples less than 18 mg P kg^{-1} from the eastern two-thirds of Kansas submitted to the KSU Soil Testing Lab over the last 47 years (Unpublished data, KSU Soil Testing Lab).



The significance of samples below the critical value of 20 mg P kg^{-1} level (defined by Leikam et al., 2003) is that a response may be expected when the soil test P is below the critical level. Using the Kansas P data which was initially used to define the P critical level, Mengel (2006) calculated a 71% average crop yield response in Kansas soils containing less than 5 mg P kg^{-}

[1](Table 1.1). At soil test levels of 15 to 20 mg P kg^{-1}, crop yield decreases averaged 8% and occurred one third of the time. With 50% of samples currently deficient in P, crop yields in Kansas can be reduced significantly unless supplied with adequate amounts of P fertilizers.

Table 1.1 Soil test phosphorus level and frequency of P response in Kansas crop production (Mengel, 2006).

Soil Test P Level (ppm)	Frequency of Fertilizer Response	Percent Yield Increase	
		Average	Range
<5	95-100%	71%	20-620%
5-10	80-90%	28%	0-185%
10-15	50-70%	8%	0-100%
15-20	30-50%	8%	0-40%
>20	<30%	2%	0-13%

No-tillage and reduced tillage production systems are increasing in popularity in Kansas and although these systems present challenges for P management, they are very effective in soil moisture conservation. The value of water in no-tillage and reduced tillage systems in Kansas has been thoroughly studied by Stone et al. (2006 a&b). Stone et al. (2006a) concluded that no-tillage is not only more effective at capturing precipitation than conventional tillage, but is also superior at retaining the water. However, with no-tillage production systems comes nutrient (specifically P) stratification, which has become an increasingly important topic to producers in the Great Plains region. Nutrient stratification refers to the non-uniform distribution of nutrients with depth, with higher concentrations of the nutrient (usually P and K) near the soil surface. In no-tillage systems, P and K stratification are the result of surface application of non-mobile nutrients (Eckert, 1985; Tyler and Howard, 1991; Morrison and Chichester, 1994; Mullen and Howard, 1992) and decreased mixing of the fertilizer applied on the soil surface (Griffith et al., 1977; MacKay et al., 1987; Karlen et al., 1991; Robbins and Voss, 1991). Phosphorus uptake by plants deep in the soil followed by decomposition and release of P from residue also increases surface P concentration (Shear and Moschler, 1969; Griffith et al., 1977; Ketchenson, 1980; Mackay et al., 1987; Karathanasis and Wells, 1990; Karlen et al., 1991). When no-tillage production systems were first gaining popularity, many agronomists were concerned that nutrient stratification would be problematic and would force producers to practice deep tillage periodically to decrease the effects of stratification. During this time frame (1960's and 1970's), several studies showed inconsistent, small decreases in P or K uptake by crops due to stratification (Singh et al., 1966; Moschler and Martens, 1975; Belcher and Ragland, 1972).

Traditional soil test sampling and recommendations of sampling the top 15 cm of soil in a single composite sample may not represent the P content and P availability in a stratified no-till soil. When P stratification is known to exist, soil sampling methods are questioned. Many agree that the critical location to sample for P in the soil is the zone where roots are concentrated and plants are able to take up P at a time when they can best utilize it. The factors that influence this include: location of soil P, area of root proliferation for the uptake of P, and depth of soil moisture for proper movement of P to the root zone and uptake of soil P. Naturally, producers' first concern is that stratification of P near the soil surface would lead to decreased crop yields due to decreased P content at soil depths where moisture is present in the soil profile.

The following literature review highlights the research conducted on P placement or studies related to P stratification in agricultural production systems. The vast majority of this work has been conducted in humid environments generally east of Kansas and often in corn and soybean production systems. The climates of these regions differ substantially from the variable conditions present in Kansas. This affects critical conditions such as crop stress and soil moisture variability encountered in the more arid environment in Kansas and makes this study unique from previous studies.

The objective of this chapter is to highlight the previous research related to agricultural crop production and the fundamental aspects of P utilization, application, and stratification.

Literature Review

Phosphorus- Historical Overview

Phosphorus history dates back to 1699 when Henning Brand, German chemist, discovered a white, waxy solid substance while trying to transform base metals to gold. He later isolated P from urine. When the P vapor was reacted with oxygen, it produced a phosphorescent glow. Therefore, it was given the name phosphorus – *phos* meaning light and *phorus* meaning bringing (Greek). Today, P is recognized as a non-metal that belongs to group 5A of the periodic table of elements and appears as a white or red solid and is a product of phosphate mineral rock known as apatite.

Historical P deficiency challenges were dealt with by the option of relocating to produce crops from land that had not yet been depleted of its nutrient supply. Forested land was cleared and burned for conversion to agricultural production. Nutrients (including P) were concentrated and deposited on the soil surface by plants over long periods of time, increasing the fertility and enhancing crop production. Additionally, soil heating during the burn process aided in the transformation of unavailable P to mineral forms that were available to plants. As arable land became scarce and as world population grew, the opportunity for relocation decreased. When the available P and other nutrients were depleted, P had to be applied to sustain crop production.

Sources of P fertilizer have changed dramatically over time as the original sources of P for agricultural use were phosphate rock and organic materials such as manures and night soil, acidulated bones and guano. After the 1840's, guano was imported into North America and England from the coastal regions of Peru as a P fertilizer (Jacob, 1964). In 1842, John B. Lawes and James Murray patented the process for the production of superphosphate by adding sulfuric acid (H_2SO_4) to bone and apatite (Jacob, 1964). Ordinary superphosphate is produced by reacting sulfuric acid with phosphate rock to form phosphoric acid. Then, the phosphoric acid reacts with phosphate rock to form monocalcium phosphate. The chemical reaction follows:

$$Ca_{10}F_2(PO_4)_6 + 7H_2SO_4 + 3H_2O \rightarrow 3Ca(H_2PO_4)_2 \bullet H_2O + 7CaSO_4 + 2HF$$

Ordinary superphosphate was the dominant P fertilizer used world-wide for over 100 years. This product is still preferred in many tropical areas with highly weathered soils where gypsum is a source of both calcium and sulfur.

At about the same time (1837), phosphate rock was discovered in the USA (South Carolina) and became an important P fertilizer for Midwest agriculture. Finely ground rock phosphate was a primary P source and applied to many soils throughout the eastern half of the US prior to World War II.

Germany began producing triple superphosphate (TSP) as early as 1870 (Jacobs, 1964), which became much more popular as a fertilizer source in the 1950's due to the increased production of phosphoric acid and reduced transportation costs per unit of P. Triple superphosphate is produced by reacting phosphate rock with phosphoric acid. The chemical reaction for production of TSP follows:

$$Ca_{10}F_2(PO4)_6 + 12H_3PO_4 + H_2O \rightarrow 9Ca(H_2PO_4)_2 \bullet H_2O + CaF_2$$

In the early 1900's, the production of ammonium phosphate fertilizers became common. This resulted in the production of monoammonium phosphate (MAP) and diammonium phosphate

(DAP) (Young and Davis, 1980). Diammonium phosphate is produced by reacting each mole of phosphoric acid with two moles of ammonia. The chemical reaction for DAP follows:

$$H_3PO_4 + 2NH_3 \rightarrow (NH_4)_2HPO_4$$

Monoammonium Phosphate is produced by adding one mole of ammonia to one mole of phosphoric acid. The chemical reaction follows:

$$H_3PO_4 + NH_3 \rightarrow (NH_4)H_2PO_4$$

Although liquid phosphate sources were produced as early as the 1920's, significant production and use did not occur until the 1950's due to improvements of P solutions being near neutral in pH (Van Buren, 1979). Ammonium polyphosphate (APP) is produced by heating two orthophosphoric acid molecules, which combine to form a pyrophosphate molecule and water. The production of ammonioum polyphosphate increased after the development of the 'T' reactor by the Tennessee Valley Authority in 1972. In this process, wet phosphoric acid is reacted with anhydrous ammonia in a stainless steel pipe. The heat produced by this reaction (340-370°C) causes water to evaporate and thus concentrates the final product to a greater phosphorus concentration. The heat producing reaction was the limitation to production before 1972 because other heating methods (e.g. electric) were cost prohibitive (Meline et al., 1972). The chemical formula for ammonium polyphosphate follows:

$$6H_3PO_4 + \text{Heat} \rightarrow H_4P_2O_7 + H_5P_3O_{10} + H_3PO_4 + 3H_2O_{(steam)}$$

$$8NH_3 + H_4P_2O_7 + H_3PO_4 \rightarrow (NH_4)_3HP_2O_7 + (NH_4)_3H_2P_3O_{10} + (NH_4)_2HPO_4$$

Chemical equations were adapted from Hedley and McLaughlin (2005).

The USA is still the largest producer of phosphate rock accounting for 21% of the world production, with nearly half the US phosphate production exported (Jasinski, 2000). Currently, the common P fertilizers in the Great Plains (USA) region include TSP, DAP, MAP, and APP.

Environmentally, P content in soil has caused increased concern because high soil test P increases the risk of P loss (Johnson et al., 2005). While P is needed in adequate quantities for optimal crop production, it has also been associated with eutrophication of surface water bodies. Research in east-central Kansas by Janssen et al. (1996) showed that conventionally tilled plots lost 2 kg P ha^{-1} $year^{-1}$ as a result of erosion and no-tillage plots lost 0.5 kg P ha^{-1} $year^{-1}$. However, Janssen et al. (1996) also found that bioavailable P losses were higher from no-tillage plots (138 g ha^{-1}) than conventional plots (35 g ha^{-1}) and attributed the difference to greater amounts of P near the soil surface in the no-tillage system. Build-up of P in agricultural soils has been accredited to large proportions (80-90%) of P from fertilizer sorbed on soil particles and unavailable to most plants (Gerke et al., 1994; Jones, 1998). However, this sorbed P is in equilibrium with P in the soil solution and is critical as a source of P to replenish P in solution removed by plant uptake. Yli-Halla et al. (1995) showed the P status of the surface 0-10 cm controlled the dissolved P concentration in runoff. More total P creates more environmental concern, but total P and available P content for plants as measured by most soil test methods are very different.

Since soil test P data summaries are available over large areas, research has been conducted to determine if there is a relationship between soil test P and P loss from soil in runoff. Pote et al. (1996) found statistically significant relationships between soil test P content (by Olsen, Bray-Kurtz, and Mehlich-3 extraction methods) and dissolved reactive P in runoff. Other work has shown similar relationships with Mehlich-3 extractable P, but used different equations representing this relationship for grassed areas and crop land (Sharpley et al., 1994). The environmental concerns have led to the establishment of both agronomic and environmental threshold values in many states. Agronomic thresholds are the maximum soil test level at which fertilizer P is recommended, while environmental thresholds are the maximum soil test levels at which P containing waste products, such as animal manure, can be applied to land for disposal purposes. Of the states using Mehlich 3 (including Kansas) as the accepted soil test method, the agronomic threshold ranges between 30 and 50 mg P kg^{-1}. In the same states, the environmental threshold is between 130 and 200 mg P kg^{-1} (Sharpley et al., 2002). The current thresholds for Kansas are 50 and 200 mg kg^{-1}Mehlich-3 extractable P for agronomic and environmental limits respectively (Leikam et al., 2003).

Plant Phosphorus

Phosphorus is considered second only to nitrogen as the most important inorganic nutrient limiting plant growth (Vance et al., 2003). Batjes (1997) calculated that 5.7 billion ha worldwide are deficient in P resulting in decreased crop yields. Phosphorus is involved in primary chemical and metabolic reactions in plants. A list of five functions of P in plants provided by Frausto da Silva and Williams (1991) follows:

1. It is a part of large molecules (DNA, RNA, phospholipids).
2. It is a carrier of substrates and chemical energy.
3. It is used in cellular signaling.
4. It is used to modify proteins.
5. It is a part of biominerals.

When P is limiting, plants translocate P from old tissue to new tissue to better use the P within the plant (Duff et al., 1991; Barioloa et al., 1994), thus causing deficiency symptoms on the older plant tissue. The deficiency symptoms for plants may vary depending on plant species, but generally appears as slow growth, relatively underdeveloped root system, thin, spindly stems, and bluish-green leaves becoming a red to purple color with severe deficiency.

Phosphorus Uptake

Phosphorus is taken up by plant roots as phosphate, primarily in the form of $H_2PO_4^-$ (Vance et al., 2003). When plants experience P deficiency, they increase the volume of soil explored by the roots (increase in root surface area), which increases the available P to the plant. Changes in root area occurr via increased lateral root growth in shallow soil where P is more highly concentrated coupled with decreased primary root elongation (Thomas and Frye, 1984; Lynch and Brown, 2001; Williamson et al., 2001; Linkohr et al., 2002; Hodge, 2004), increased relations with mycorrhizal fungi, and larger number and length of root hairs (Jungk, 2001; Ma et al., 2001). Plants that have a coarse root system (few root hairs) increase P uptake dramatically by mycorrhizal associations (Grahm and Eissenstat, 1994). Root hair, number, and length are considered an adaptation to increase P uptake (Bates and Lynch, 2001) and increase both in length and number when P deficient conditions arise (Schmidt, 2001). An excellent example of this is that barley (*Hordeum vulgare*) genotypes with long root hairs exhibit yield advantages above those genotypes with root hairs half as long (Gahoonia and Nielsen, 2004). Phosphorus supply has also been shown to have a direct effect on biomass partitioning (Ryser et al., 1997; De Groote et al., 2001); moreover, P stress causes most species to allocate more biomass to roots rather than above ground plant parts (Brouwer, 1983) as in grain crops (Steingrobe et al., 2001). However, there are some species such as *Lupinus* (herbs and shrubs) that are known as extremely P efficient, which do not significantly alter biomass partitioning due to P (Keerthisinghe et al., 1998; Pearse et al., 2006).

Along with morphological changes in plant roots, P deficiency also causes plants to alter the phosphate transport ability of root cells (Lee, 1993) by regulating phosphate transporters (Smith et al., 2003). These phosphate transporters are present in root hairs, where they will be most effective for acquiring phosphate (Mudge et al., 2002; Schünmann et al., 2004). Roots also modify the rhizosphere for heightened uptake of P from the soil by exudation of organic acids (López-Bucio et al., 2000) and enzymes (Miller et al., 2001).

Plants are known to have competition, most obvious being above ground competition for light, but below ground competition is equally important and includes both water and nutrients (Rubio et al., 2001). Robinson (1991) explains that below-ground competition for nutrients that move by diffusion occurs when the zones of nutrient depletion overlap. This results in decreased uptake of the nutrient because nutrients that move by diffusion are taken up at the root surface, which creates a concentration gradient and continues to decrease the nutrient in the depletion zone (Rubio t al., 2001). Nye and Tinker (1977) classified the depletion zone as the length at which the nutrient concentration is reduced to 10 % of the concentration of the bulk soil. The depletion zones can be measured, but when root distribution is heterogeneous, additional difficulty and uncertainty is added (Barber, 1995; Smethurst and Comerford, 1993). Rubio et al. (2001) showed the radial distribution of basal roots was not affected by P supply or inter-plant competition, but P diffusion significantly affects inter-plant competition. Fitter et al. (1991) and Lynch (1995) identified two prime factors that control root competition for P as the root architecture or the spatial pattern. Regardless of spatial distribution of roots, when below-ground competition is low, plants are more efficient at P uptake because root overlapping is minimal and more volume of soil can be accessed and thus P is more available P (Rubio et al., 2001). Some plants have been classified as P mobilizing species as a result of high amounts of root exudates. Nuruzzaman et al. (2005) and Kamh et al. (2002) found that when growing wheat and corn after a legume, P uptake increased, which was attributed to P mobilization, not the effects of nitrogen fixation.

A study that combines the effects of uniform and stratified soil P, along with shallow, intermediate, and deep root structure was conducted by Rubio et al. (2001). This study used a simulation model that utilized two soils, one they denoted as soil A with homogenous P, and the second labeled B that had more P in the surface and decreased with depth (Figure 1.2). They went on to find that the root architecture affected P uptake, but when soil P was stratified, the competition among plants heightened. It is also interesting to note that Figure 1.2 shows P uptake was greater for P stratified soil and that P uptake was greater for shallow roots and least for deep roots. Although effects of water and diffusion of P were held constant, the conclusion remains the same that the location of soil P effects P uptake when roots are present in that zone of the soil.

Figure 1.2 Soil P distribution and effect of root architecture on P uptake (from Rubio et al., 2001).

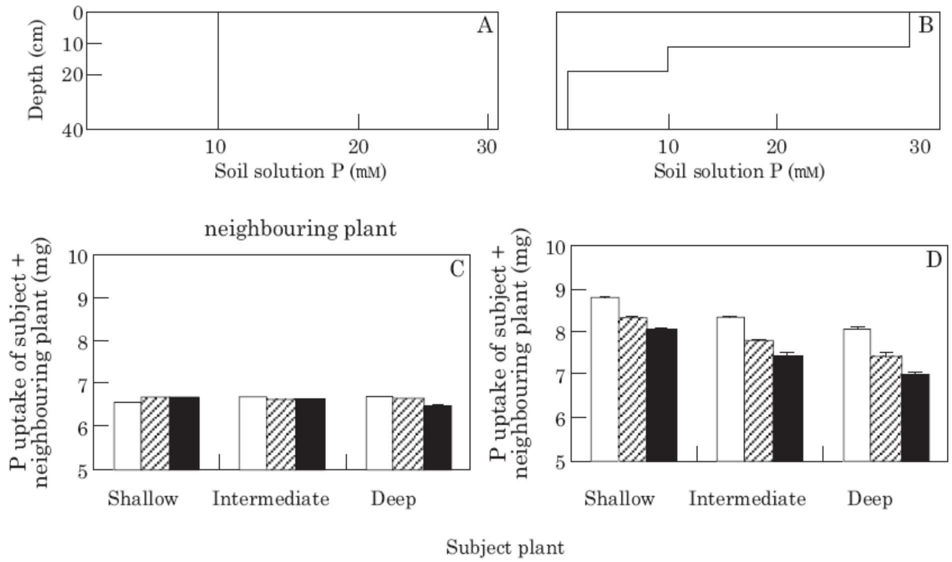
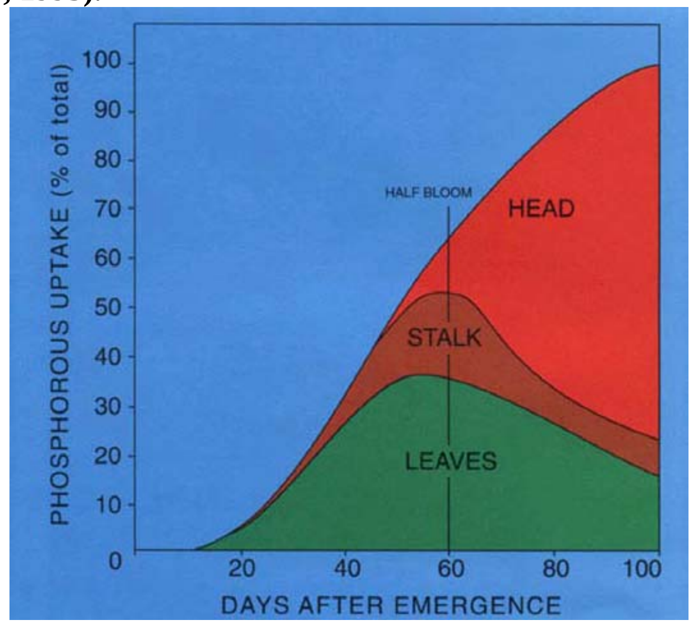


FIG. 9. Two simulated soil profiles, showing homogeneous (A) and heterogeneous (B) soil phosphorus distribution; and P uptake of subject plant and subject plus neighbouring plant as affected by root architecture [shallow (□), intermediate (▨) and deep (■), soil type [homogeneous (C) and heterogeneous (D)] and competition (all combinations of root architectures). Data are means of five replicates ± s.e.m.

The accumulation of P over the life cycle of plants follows the accumulation of dry matter in plants (Hanway and Olson, 1980). Dry matter accumulation is exponential during vegetative growth until there is enough leaf surface area to intercept sufficient sunlight. After this time, biomass accumulation and thus P uptake remain relatively constant (Hanway and Olson, 1980). Vanderlip (1993) described nutrient uptake and distribution among plant parts in grain sorghum (*Sorghum bicolor* L., Figure 1.3). From Figure 1.3, it is clear that during the early portion of the life cycle of sorghum (or other cereal grain crops) the majority of the P is present in the leaves.

Figure 1.3 Phosphorus uptake (% of total) and distribution over the life cycle of grain sorghum (Vanderlip, 1993).



Mengel and Barber (1972) found that the rate of P uptake per unit root in corn decreases dramatically throughout the vegetative growth phase. Thus, it is intuitive that the direct effect of P application and/or placement will show the greatest responses in early stages of plant growth. However, in a P stratified soil, early plant uptake may occur from a shallow depth and thus a response to deep placement of P may not be found. Jungk and Barber (1975) studied the effects of placing half of a corn plant's roots in a P solution and half in a solution without P and the effects of trimming corn roots to reduce the amount of roots available for P uptake. Both procedures did not result in an increased demand for P, showing that the entire root system does not have to be in contact with P to supply ample P to the plant.

Plant Analysis

Plant analysis has been used to monitor P concentration in plants during vegetative growth (Walter and Peck, 1975; Eckert and Johnson, 1985; Reeves et al., 1986; Mallarino, 1996) and to evaluate factors that influence plant growth (Melsted et al., 1969). There are specific challenges with regard to plant sampling. First, nutrient concentration changes with the plant species, age of plant tissue, position of the sample on the plant, concentration of other nutrients, climatic factors, and soil conditions (Mills and Jones, 1996). Generally, the most recently developed mature leaf is most appropriate for routine plant analysis. If the objective is to detect P deficiency through plant testing, older leaves should be sampled as the P will translocate to younger tissue allowing for a more sensitive deficiency diagnosis (Mills and Jones, 1996). Alternatively, if critical P levels, defined as the concentration of P in a specific plant part at which growth starts to decline (Ulrich and Hills, 1967) are being identified, the uppermost leaf should be used. Mills and Jones (1996) discuss the non-uniform distribution of elements in leaves and that P tends to concentrate near the leaf tip. Also, leaf blades and leaf margins have higher concentrations of P than the midrib. Early work (1950's to 1970's) focused heavily on nutrient composition of plant samples to establish these critical values. Melsted et al. (1969) explained that accuracy and availability of plant analysis was well accepted by the general public, but cautions the value of this analysis is only as good as the interpretations to field conditions. Melstead et al. (1969) continues to say plant nutrient content is typically more sensitive in terms of crop response to environmental changes than yield, but is increasingly more difficult to understand. Therefore, much work has been conducted on establishing critical values for plant samples (Tyner, 1947; Viets et al., 1954; Ellis et al., 1956; Reichman et al., 1959; Dumenil, 1961; Hanway and Weber, 1971; Baker and Tucker, 1973; Mills and Jones, 1996). Table 1.2 includes recent interpretative data for plant analysis for all reported growth stages on crops used in this study.

Table 1.2 Phosphorus sufficiency ranges for all crops used in this study and at all available growth stages reported by Mills and Jones (1996).

Crop	Growth Stage	Plant Part	P Sufficiency Range (%)
Corn	< 30.5 cm tall	whole plant	0.30-0.50
	prior to tasseling	12 leaves below whorl	0.25-0.45
	silking	ear leaves	0.25-0.50
Soybean	prior to pod set	mature leaves	0.25-0.50
Grain Sorghum	23-39 days old	whole plant	0.30-0.60
	37-56 days old	mature leaves	0.13-0.25
	bloom stage	3rd leaf below head	0.23-0.35
	dough stage	3rd leaf below head	0.15-0.25
Winter Wheat	prior to heading	top 2 leaves	0.20-0.50
	head emergence	whole plant	0.20-0.50

From Table 1.2, it should be noted that the sufficiency values are expressed in a range, and not as a single value. Melsted et al. (1969) described that critical values are typically listed as a range because although small decreases from a single critical value is the beginning sign of a nutrient imbalance, the decline usually does not result in a growth or yield depression until an even greater decrease in nutrient concentration occurs. The difficulty is, as Melsted et al. (1969) explained, if a plant analysis results in a particular value (their example was 0.28% P) and the details of the variety and site conditions are not known and adjusted for, 0.28% may actually represent any value from 0.23 to 0.33% for interpretative purposes. This means the plant would be approaching a P deficiency at the lower portion of the range and would be sufficient at the upper end of the range. For this reason, it has been very difficult to establish fertilizer recommendations based on plant analysis.

Research has been conducted in Iowa to monitor high soil P with plant analysis in the adequate P to excessive P range (Mallarino, 1995). This work showed that plant analysis can not be used to evaluate high soil P as plant P maximized at soil test levels below the maximum observed in the field. They also noted the value of the ear leaf P test for diagnosing P deficiency was limited by the variability in P concentration imposed by factors other than P availability. However, in a later study (Borges and Mallarino, 1998) Mallarino proposed using plant analysis as an alternative to soil analysis and specifically suggested it be used to differentiate spatial variability of nutrients because it might be less affected by small scale variability and variations in sampling depth. Faranzen and Peck (1995) evaluated the spatial variability of P with plant analysis to determine how well P from plant analysis agreed with soil test P. This study showed that variability in a corn field was greatest for soil test P and least for corn ear leaf P concentration with the variation in early stages of corn (V5 growth stage) P concentration closer to that of the ear leaves. Generally, there were weak, but significant relationships between soil test P and plant samples in all three years of this study. However, the early plant P and late plant P were only significantly correlated in two of the three years. Borges and Mallarino (1998) conducted a similar study but related the variation of early growth and nutrient uptake to soil test P (Table 1.3).

Table 1.3 Relationships between plant variables and soil test P and K measured by grid sampling (Borges and Mallarino, 1998).

		Correlation with soil test P			Correlation with soil test K		
Crop	Field	DW†	PC	PU	DW	KC	KU
		---------- Correlation coefficient ----------					
Soybean	1	-0.07	0.02	-0.07	0.20	0.64*	0.82*
	2	0.42	0.48	0.61*‡	-0.10	0.77*	0.55*
	3	0.11	0.18	0.19	0.32*	0.53*	0.54*
	4	0.13	0.27	0.27	0.11	0.17	0.15
Corn	5	0.23	-0.12	0.22	0.75*‡	0.87*	0.85*‡
	6	0.54*	0.40	0.60*‡	-0.63*	0.44	-0.22
	7	0.78*	0.62*	0.86*	0.70*	0.66*	0.80*
	8	0.57*	0.09	0.70*	0.51*	0.54*	0.70*

*Significant coefficients at $P \leq 0.05$.

†DW=dry weight, PC=P concentration, PU=P uptake, KC=K concentration, and KU=K uptake.

‡Trends were curvilinear increasing to a maximum (trends were linear in all other instances).

They concluded that plant P concentration was rarely related to grid-sampled soil test P and that P uptake was only related to grid-sampled soil test P in one of four soybean fields but in three of four corn fields. Interestingly, the only fields where dry weight was related to soil test P were the fields where P uptake was related to soil test P. Borges and Mallarino (1998) also established the same relationships from two intersecting transects. Table 1.4 shows the relationships generated from these transects, which displays all soybean fields and three of four corn fields had significant correlations between P uptake and soil test P.

Table 1.4 Relationships between plant variables and soil test P and K from two transects (Borges and Mallarino, 1998).

Crop	Field	N†	Correlation with soil test P			Correlation with soil test K		
			DW‡	PC	PU	DW	KC	KU
			Correlation coefficient					
Soybean	1	99	0.38*§	-0.14	0.35*§	0.20*	0.60*§	0.47*
	2	100	0.28*§	0.35*§	0.38*§	0.11	0.32*	0.26*
	3	100	0.36*	0.36*§	0.40*§	0.40*	0.61*	0.61*
	4	100	0.37*	0.02	0.24*	0.28*	0.33*	0.38*
Corn	5	90	0.37*	0.14	0.41*	0.50*§	0.11	0.41*
	6	80	0.14	0.26*	0.18	-0.19	0.24*	-0.06
	7	78	0.71*§	0.30*	0.73*	0.41*	0.58*§	0.52*
	8	100	0.21*	0.25*	0.30*	-0.08	0.62*	0.47*

*Significant coefficients at $P \leq 0.05$.
†N=Number of observations for two transects combined.
‡DW=dry weight, PC=P concentration, PU=P uptake, KC=K concentration, and KU=K uptake.
§Trends were curvilinear increasing to a maximum (trends were linear in all other instances).

Likewise, plant P content was more closely related to soil test P at the transect points to the grid sampling of the field, with half of the soybean fields and three of the four corn fields significantly correlated to soil test P at the sampling points. Again, all fields that had a significant relationship between P uptake and soil tests levels also showed a significant relationship between dry weight or biomass production and soil test level. To more fully understand the connection between P uptake, dry weight, and soil test P, they conducted factor analysis and concluded that plant growth and P uptake had a strong association, but there was no consistent relationship between plant dry weight and soil test P. Clearly, there is a notable difference between the two datasets as a result of the sampling procedures (e.g. dry weight and P uptake differences between the two sampling procedures). They attributed this to the ability to detect small scale variations in soil and plant samples collected using transects (small scale, 2 m^2 sampling area every 3 m) rather than the gross scales associated with grid samples (0.14 ha). In a later study, Sawchik and Mallarino (2008) conclude early soybean growth variation as measured by dry weight has more influence on P uptake than P concentration in the plant tissue. In their P study, they further stated that high variation in early soybean growth is not necessarily related to soil test P. Keep in mind all of Mallarino's work was focused on using plant anaylsis to assess excess P in the field, and was conducted on fields with broad ranges in soil test P levels that went far beyond the established P critical levels. Skudra and Skudra (2004) also conducted a study focusing on the relationship between P concentration in winter wheat tissue and soil P. They found the only correlation between plant P concentration (in the leaves) and soil test P was during shoot development of the wheat plant, and when the soil was sampled at the 0-20 and 20-40 cm depths.

P Removal by Crops

Crop P removal data for Kansas was reported by Leikam et al. (2003). Table 1.5 was adapted from data presented by Leikam et al. (2003) and shows the expected P removal in corn, soybean, sorghum, and wheat.

Table 1.5 Estimated crop P removal in grain for corn, soybean, sorghum, and wheat (Adapted from Leikam et al., 2003).

Crop	P Removal (g P kg^{-1} grain)
Corn	2.59
Soybean	5.85
Sorghum	3.14
Wheat	3.66

The projected P removal is an estimate of the amount of P that will be removed from the soil when the crop is harvested and the grain is removed. The estimates of crop removal is used in the KSU soil test P build and maintain fertilizer recommendation system to assure replacement of removed P. Iowa State University researchers calculated nutrient removal in corn grain and stover and demonstrated that 33.0 kg P ha^{-1} was removed in corn grain and an additional 9.4 kg P ha^{-1} was in the stover (Sawyer and Mallarino, 2007). Thus, after harvest, 9.4 kg P ha^{-1} that was taken up from varying depths in the soil was deposited on the soil surface after decomposition of the stover. This causes a relocation of soil P from deep in the soil to the soil surface, and creates nutrient stratification.

Soil Phosphorus

Phosphorus is recognized as a very immobile plant nutrient in soil. Generally, the increased weathering of soils over geologic time decreases the total and available P content in soil (Walker and Syers, 1976; Crews et al., 1995; Richardson et al., 2004). There are three methods by which phosphorus comes in contact with plant roots for uptake. First, mass flow, the transport of dissolved P in soil water moving to plant roots may supply as much as 5% of the required plant P. Root interception, or the incidental contact of plant roots with P in the process of root growth and exploitation of the soil may provide as much as 2.5% of the needed P (Lambers et al., 1998). The final method that supplies the majority of P to plant roots is diffusion. Although this is the primary delivery method of P to plant roots, the diffusion coefficients for P in soil are much lower than the coefficients of other nutrients (Clarkson, 1981).

When P fertilizer is applied on or in soil, chemical and physical reactions take place that depend on the source or type of fertilizer applied. Early literature identifies three ways by which initial wetting of a P granule can occur: rainfall, capillary flow into the fertilizer granule, or water vapor transfer (Lawton and Vomocil, 1954; Lehr et al., 1959; Williams, 1969). In dry soils, vapor pressure at the granule surface is lower than dry soil, causing water vapor to diffuse to the granule (Lawton and Vomocil, 1954). The diffusion of P in dry soil is very slow (Turner and Gilliam, 1976; Bhadoria et al., 1991). In moist soil, water moves to the granule by mass flow and diffuses phosphate away from the granule. The moisture uptake by the granule is heavily affected by the size, shape, and porosity of the granule (Williams, 1969).

Methods of P placement have been considered and evaluated to reduce the severity of P stratification. Background information needed before using placement methods is whether or not the location of the P fertilizer (i.e. distance from the plant) affects the uptake of P because it is well known that P fertilizer moves a very short distance from the point of application (Sharpley, 1986). Sleight et al. (1984) suggested one way distance of a P fertilizer band from the plant affects fertilizer use is by changing the probability of plant root interception and contact with the fertilizer. The second way distance affects access to P is by the time it takes for the roots to come in contact with the P fertilizer, which has been demonstrated in wheat research (Sutton et al., 1983). Some research suggests a single root could supply a plant with its P needs (Kissel and Ragland, 1967) since roots proliferate in zones of high fertility, by increasing the number of root branches and fine lateral roots (Anghinoni and Barber, 1980). These fine lateral roots have extremely high root surface area that increases the ability to absorb P (Duncan and Ohlrogge, 1958). Early work by Lawton and Vomocil (1954) showed P from a superphosphate granule moved about 2.5 cm, but noted P from larger granules moved more. Additional research found P movement is greater in sand than in a loam soil (Sleight et al., 1984). Furthermore, when Eghball and Sandler (1989) studied the distribution of applied P fertilizer in irrigated corn, they found fertilizer moved from the location it was placed in the soil out in all directions to "make a near perfect sphere." They went on to find fertilizer P increased in the plant more, the closer the fertilizer was located to the plant, which was attributed to earlier and longer contact between roots and fertilizer and the probability of root contact with fertilizer. However, effect of fertilizer distance was dependant on the age of the plant. The older the plant, the less effect of fertilizer distance on both plant P and biomass production. Phosphorus application rate also affected plant P because higher rates allowed for more P to remain available longer. So, as proximity and rate increase, there is an increase in early plant P. This information leads to the deduction that placing P fertilizer where it has the greatest potential for uptake should be the best management strategy. However, the location where plant roots can access the P fertilizer will be dependant on factors such as soil moisture, plant row spacing and populations and other site conditions.

Managing Phosphorus

Soil Testing

The most common method of determining plant available P in the soil is by soil testing. To be useful: 1) the soil sample must adequately represent the area it was taken from, 2) the soil test must provide an accurate estimate of the plant available P, 3) the soil test P result should be well correlated (crop response at a given soil test value) and calibrated (probability of crop response to nutrient application at a given soil test level), and 4) a reliable and consistent recommendation equation must be developed based on the soil test.

Two very important components of any useful soil test are the correlation and calibration of the test. Corey (1987) indicated that although extractants used for soil tests are based on chemical properties, the relationship between the soil test value and plant response dictates the quality of the soil test, which defines soil test correlation. In a discussion regarding soil test P correlation, Fixen and Grove (1990) showed correlation data from the following work: Baker and Hall (1967), Blanchar and Caldwell (1964), Bowman et al. (1978), Dalal and Hallsworth (1976), Fixen and Carson (1978), Griffin and Lorton (1970), Holford (1980), John et al. (1967), Labhsetwar and Soltanpour (1985), Lathwell et al. (1958), Luscombe et al. (1979), Matar and Samman (1975), Mehlich (1978), Oko and Agboola (1974), Olsen et al. (1954), Onken et al. (1980), Thompson and Pratt (1954), van Diest (1963), van Raij et al. (1986), Wendt and Corey (1981), Williams (1966), Zubriski (1971). From their discussion, it is clear that different soil properties (namely pH) heavily influence the ability of soil tests to correlate with available P. They show some studies where the Olsen Extractant (0.5 *M* $NaHCO_3$ at pH 8.5) is superior to the Bray P_1 Extractant (0.03 *M* NH_4F + 0.025 *M* HCl) in calcareous soils, while other studies show that these extractants performed similarly. Interestingly, in areas like Illinois and Indiana where rock phosphate was historically applied, the Bray P-2 soil test is still used to identify levels of P that was applied from rock phosphate because current extraction methods do not account for this form of P. Fixen and Grove (1990) continue to show examples where soil properties and soil test extractants correlate very differently leading to the conclusion that soil test correlation must be conducted using extracting procedures appropriate for a geographic area and verified with local research. Methods of establishing critical soil P content, the point where soil test P can provide adequate P to support crop growth, were evaluated by Mallarino and Blackmer (1992). They evaluated a number of procedures including: Cate-Nelson (Cate and Nelson, 1965), linear plateau, quadratic plateau, quadratic, and exponential Mitscherlich equations. Based on this study, they concluded the Cate-Nelson procedure was best at establishing critical values for fertilizer recommendations. Once correlation studies are conducted, calibration work must follow.

Calibration is the process of establishing fertilizer rate recommendations, and is the result of evaluating the probability of getting a growth or yield response to specific rate of applied nutrient at a given soil test level. Calibration is typically based on field response data and typically uses relative yield or normalized yield, rather than actual yield, because relative yield eliminates many uncontrollable factors and allows pooling of data from sites with varying yield potential. Similar to correlation data, calibration work should be conducted under similar conditions in which the test will be used. Studies show that critical P levels vary spatially (generally increasing from west to east in the US) and temporally (year to year) (Cox, 1992).

No-tillage and reduced tillage production systems are challenging for soil testing because it is difficult to establish soil sampling strategies both in terms of location and depth of sample collection (Bordoli and Mallarino, 1998). Bordoli and Mallarino (1998) suggest this is an issue because the accumulation of P at the soil surface could decrease nutrient availability, specifically if dry conditions persist near the soil surface, and the use of band placement of fertilizer to increase fertilizer efficiency, which are not disrupted and distributed throughout the soil by tillage as in more conventional systems. However, as Barber (1971) noted, increased shallow soil moisture in these no-till production systems may actually increase root activity and nutrient uptake at the onset of dry periods. So, much of the difficulty in understanding these systems is that results are often contradictory due to interactions of fertilizer placement, management systems, and climate (Bordoli and Mallarino, 1998).

Traditional P Application

Welch et al. (1965) provided an overview of phosphorus placement. They indicated that before modern P fertilizers with relatively high P concentration were available, low rates of P fertilizer with low P concentration was applied in a band near the seed. However, with improved, concentrated P fertilizer sources, many more options for fertilizer placement became available. Currently, the ‘typical’ application method for P is broadcast on the soil surface with or without tillage as a tool for incorporating the P into the soil. The importance of tillage was to distribute the P evenly in the tilled zone to allow for an enriched area for plant uptake of P. Currently, our soil sampling methods and nutrient recommendation systems hinge on the traditional tillage depth of 15 to 20 cm. The logic behind soil sampling to tillage depth is to sample the zone of tilled and mixed soil to provide a uniform soil sample for analysis and interpretation.

Studies conducted in eastern parts of Kansas in regions of higher soil moisture have demonstrated that surface application and/or high soil test P in the surface portions of the traditionally tilled soil often increase yields (Belcher and Ragland, 1972; Hargrove, 1985; Moscheler et al., 1972; Howard and Tyler, 1987). Additionally, some have demonstrated that incorporation of P fertilizer has actually decreased yield because of nutrient uptake occurring in shallow soil depths that are lower in P concentration due to soil mixing (Hargrove, 1985; Moscheler et al., 1972). However, Howard et al. (2002) showed mixing P fertilizer by disking produced higher yields than surface applications in no-tillage and yields responded to higher rates of P when fertilizer was mixed with the soil than surface applied in a no-tillage situation.

Enhanced P Placement

Much of the placement work with P has been as starter fertilizer, bands of fertilizer applied at planting with or close to the seed, or in combination with other starter fertilizers. Starter P placement method employs fertilizer attachments on drills and/or planters to apply relatively low rates of P with the seed or close to the seed. Phosphorus applied as starter (5 cm to the side and 5 cm below the seed) on low P testing sites generally resulted in increased yields (Randall and Hoeft, 1988; Rehm et al., 1988; Eckert and Johnson, 1985; Bordoli and Mallarino, 1998) and was superior to broadcast P (Eckert and Johnson, 1985), but the effect on high soil test

P sites are inconsistent. Kamprath (1999) showed that starter applications of 19 kg P ha^{-1} kept soil test P constant over 15 years on soils with a 'very high' level of P, but noted that removing the starter application resulted in a decrease in soil test P. At this high soil test P level, there was not a yield response in corn or soybean to starter P. Earlier, Kamprath (1967) showed 8 mg kg^{-1} of extractable P (with Mehlich 1 extractant) in a high P-fixing soil was sufficient and starter fertilization did not increase yields. Rehm et al. (1988) also found starter P was not effective in high soil test P. However, Kansas research has shown starter P responses in high soil test P sites (Gordon, 1999). Touchton and Rickerl (1986) showed when starter P was applied at a rate of 19 kg P ha^{-1} on low soil test P soil, there was a significant increase in P concentration of soybean plant tissue 21-28 days after planting, but did not find a difference in high P soil. They also found soybean yields were affected by residual P and K levels and raising the P or K levels increased yields by 18%. General conclusions from studies evaluating starter application are that on low soil test P soils, yields are increased, but on high soil test P sites starter P is not needed (Ketterings et al., 2005).

Howard et al. (2002) explained (in the context of starter fertilization) banding a portion of fertilizer allows the fertilizer to be available even when drought conditions are present and where nutrient uptake by surface roots is limited. Toler et al. (2004) demonstrated this by showing soil moisture at planting determined whether or not starter P would impact yield on soils testing high in soil test P (74-120 kg ha^{-1} with Mehlich 1 extractant). Their results showed that when there was plentiful moisture, P application did not increase yield. The results by Toler et al. (2004) may explain why Gordon (1999) found starter responses in high soil test P sites in Kansas where soil moisture is generally limiting.

Barber (1980) established a long-term study to evaluate the effectiveness of residual band and broadcast incorporated application of P. He concluded since the band application was mixed with less soil and subject to less reaction with soil components, the most effective application with regard to recovery of P is the band treatment. However, crop yields were higher with the broadcast treatment, which Barber (1980) attributed to more P available to the crop root system. Borkert and Barber (1985) later showed as application rate increases, the fraction of soil that needs to be treated with P fertilizer increases. Since Dr. Stanley Barber is one of the most well respected scientists in the area of phosphorus placement and below ground interactions with the plant, it is interesting to hear his thoughts on these issues. In an interview with Fluid Journal, Barber first stated the importance of diffusion to P movement in the soil and the importance of soil water for P movement. When discussing banding, Barber identified that subsurface banding places P in the area of greater soil moisture, but the volume of soil receiving fertilizer may only be one percent. He then noted 5 to 20% of the soil volume needs to be fertilized to be effective. His rational was roots have a maximum absorption rate and increased P uptake is a direct result of more plant roots in fertilized soil. The problem is the relatively small fertilized soil volume when broadcasting P on the soil surface, but Barber noted that the soil volume could be five percent even if it is not mixed with the soil. However, fertilizer use efficiency increases when the fertilized soil volume is smaller as with band applied P (By S. Barber, http://www.nfliquidfertilizer.com/pdf/4P32-33.pdf. accessed 12/2008).

Kovar and Barber (1987) studied the recovery of P as a result of P placement on 33 soils from the US and Canada to show how placement affects P uptake and recovery and to see if soil properties and optimum placement are related. They found the best P uptake for the majority of the soils occurred when 1.7 to 5% of the soil volume was fertilized and the greatest P recovery was the result of 5% of the soil volume receiving fertilizer. They noted when P was applied in a band near the plant row (at 24 kg P ha^{-1}), about 0.5% of the soil volume was fertilized. When evaluating the relative effect of placement, they show the lower the soil test P, the greater the effect of optimum placement and conclude when soil test P is low and fertilizer rates are low, banding fertilizer gives the greatest benefit.

Application of nutrients deep in the soil (> 5 cm) has been considered better than other placement options in specific conditions. Bordoli and Mallarino (1998) classify deep application as a better practice when nutrient stratification and decreased topsoil moisture impede nutrient uptake from shallow depths. However, it should be realized that much of the benefits of deep band P placement is speculative, as little work has been conducted on deep banding in different climatic conditions to make definitive statements (Bordoli and Mallarino, 1998).

Interactions With Reduced Tillage

It is well established that reduced tillage practices influence soil water relationships. Reduced tillage increases the number of macropores, increases water infiltration, and decreases water runoff (Alakukku, 1998; Morgan, 1995). Soil moisture has been shown to affect P uptake (Mederski and Wilson, 1960; Olsen et al., 1961) because moisture influences P diffusion through the soil to the plant roots (Olsen et al., 1965; Mahtab et al., 1971; Hira and Singh, 1977). The diffusion rate of P is also less affected by soil moisture at high P levels (Mahtab et al., 1971). Mahtab et al. (1971) showed P diffusion increased with P additions because the diffusion rate is dictated by the amount of P in solution (Figure 1.4). This study also showed that P diffusion increased with clay content, which opposes previous findings (Baldovinos and Thomas, 1967). Increased clay content would increase soil buffering power, fixation capacity, and at low P contents this would have an adverse impact on diffusion. But increasing clay content would also increase aggregation and porosity, which would allow for a more direct, shorter path to the root surface. Decreased water content also increased the diffusion coefficient because the area available for diffusion to take place decreases and ions must travel a longer distance to reach a given point.

Figure 1.4 Relationship between diffusion coefficients and applied P, clay content, and water content (from Mahtab et al., 1971).

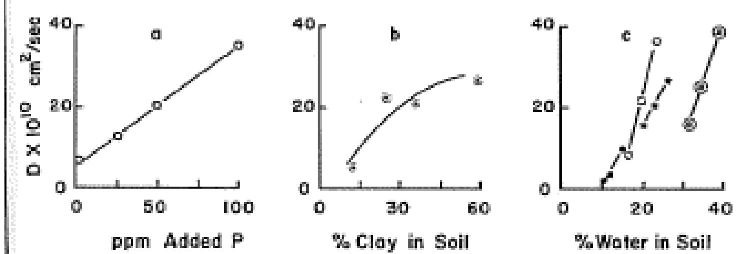


Fig. 2—Relationship between diffusion coefficients of P and (*a*) applied phosphorus for all four soils; (*b*) soil clay content for all four soils; and (*c*) percent water in soil; ○ — Norwood, ● — Intergrade I, ★ — Intergrade II, ⊛ — Miller.

Boomsma et al. (2007) made a direct connection between soil moisture and tillage systems and noted that when no-tillage conserves adequate soil moisture near the soil surface, high surface P concentration is not detrimental because of water availability near the surface for P uptake. However, when nutrient concentrations and/or moisture availability is limiting near the soil surface, plant productivity will suffer. Boomsma et al. (2007) identifies deep banding of P or K as beneficial when surface and subsoil P and K levels are low, the soil surface is dry, and low soil temperature or compaction restrict root growth to shallow soil depths.

Strip tillage is a compromise system between no-tillage practices and conventional practices. Strip till involves pulling a narrow tool through the soil to fracture and move residue. The result is a narrow band of non-residue covered and loosened soil for planting. Benefits in the tilled portion include earlier warming of soils in the tilled planting zone, and residue covered soil between the rows to improve water conservation and minimize wind and water erosion. Strip tillage also provides an opportunity to place fertilizer below the soil surface with the knife or shank used on most strip-tillage applicators.

It is well known that P is relatively immobile in the soil and that the distance and rate of diffusion depends largely on soil water content (Williams, 1971). Tillage systems that create mechanical soil mixing causes P to be mechanically moved into specific tilled zones, decreasing diffusion distances required for P uptake. In conventional tilled systems where there is uniform mixing in the soil sampling zone, P concentration is often expected to be horizontally uniform. However, research has demonstrated that vertical gradients in soil test P concentration persist even when conventional tillage (chisel plow) methods are employed (Wright et al., 2006). Schwab et al. (2006) studied the effects of tillage and annual P management on plant growth and yield in southeast Kansas. When trying to relieve stratification with tillage, effects on corn grain yield were only significant at one of three sites; there was no difference in grain sorghum yields and there was an increase in wheat grain yields with tillage. Furthermore, deep banded P increased sorghum grain yield, but had little effect on wheat or corn yield. Holanda et al. (1998) found that 0-5 cm soil P concentrations were 37, 110, and 102 mg P dm^{-3} for moldboard plow, chisel plow, and no-tillage, respectively. Lal et al. (1990) showed continuous no-tillage had significant P stratification and yearly plowing led to uniform P distribution. When they plowed for ten years followed by two years of no-tillage there was a 33% increase in the P concentration in the 0-10 cm depth. Several studies have demonstrated managing no-till grain crops to have early season nutrient availability often increase grain yields (Mackay et al., 1987; Randall and Hoeft, 1988; Mengel et al., 1992).

Summary

Factors related to P in stratified soils that are most important include: location of soil moisture, location and amount of soil and fertilizer P, and root growth and ability to take up adequate amounts of P. Many of these factors have been studied individually or together in very specific climatic conditions. However, it is intuitive that the interactions of these parameters need to be studied in a wide range of environments to evaluate the effects of moisture on different crops in field conditions.

From the above literature review, it is clear soil moisture plays an important role in the effects of nutrient stratification on P uptake and plant growth. While there has been much concern expressed over the role of nutrient stratification in no-till on crop yield, much of the current data has shown the impacts to be positive or neutral, and not negative. However, since much of this work has been conducted in areas of relatively adequate soil surface moisture, the same data needed to be collected in more dry environments, typical of Kansas. Equally important is the soil test P level. Research has long demonstrated that crop response to P fertilizer decreases as soil test P increases. The uncertainty lies in the variable concentration with depth, leading to the question of whether or not our current soil sampling strategy combined with our known critical P levels adequately represents the same probability of getting a plant (crop) response to P fertilizer.

Objectives

The objectives of this research are:

1) to determine the response of crops commonly grown in Kansas to P fertilizer applied as a starter, through broadcast, or deep band applications, particularly as soil test P, rate of fertilizer P and soil moisture varies, and

2) evaluate the impact of P placement and rate on soil test P concentration in vertically and laterally stratified soil by sampling in the crop row and inter-row spaces.

References

Alakukku, L. 1998. Properties of compacted fine-textured soils as affected by crop rotation and reduced tillage. Soil Tillage Res. 47:83-89.

Anghinoni, I., and S.A. Barber. 1980. Phosphorus application rate and distribution in the soil and phosphorus uptake by corn. Soil Sci. Soc. Am. J. 44:1041-1044.

Baker, D.E., and J.K. Hall. 1967. Measurements of phosphorus availability in acid soils of Pennsylvania. Soil Sci. Soc. Am. J. 31:662-667.

Baker, J.M., and B.B. Tucker. 1973. Critical N, P, and P levels in winter wheat. Commun. Soil Sci. Plant Anal. 4:347-358.

Baldovinos, F., and G.W. Thomas. 1967. The effect of clay content on phosphorus uptake. Soil Sci. Soc. Am. Proc. 31:680-682.

Barber, S.A. 1980. Twenty-five years of phosphate and potassium fertilization of a crop rotation. Fertilizer Res. 1:29-36.

Barber, S.A. 1991. Effect of tillage practice on corn (*Zea mays* L.) root distribution and morphology. Agron. J. 63:724-726.

Barber, S.A. 1995. Soil nutrient bioavailability: a mechanistic approach. New York: Wiley-Interscience.

Bariola, P.A., C.J. Howard, C.B. Taylor, M.T. Verburg, V.D. Jaglan, and P.J. Green. 1994. The *Arabidopsis* ribonuclease gene RNS1 is tightly controlled in response to phosphate limitation. Plant J. 6:673-685.

Bates, T.R., and J.P. Lynch. 2001. Root hairs confer a competitive advantage under low phosphorus availability. Plant Soil. 236:243-250.

Batjes, N.H. 1997. A world data set of derived soil properties by FAO-UNESCO soil unit for global modeling. Soil Use Manage. 13:9-16.

Belcher, C.R., and J.L. Ragland. 1972. Phosphorus absorption by sod planted corn (*Zea mays* L.) from surface applied phosphorus. Agron. J. 64:754-757.

Bhadoria, P.B.S., J. Kaselowski, J. Classen, and A. Jungk. 1991. Phosphate diffusion coefficients in soil as affected by bulk density and water content. Zditschrift für Pflanzenernährung und Bodenkunde 154:53-57.

Blanchar, R.W., and A.C. Caldwell. 1964. Phosphorus uptake by plants and readily extractable phosphorus in soils. Agron. J. 56:218-221.

Boomsma, C.R., M. Canepa, and T.J. Vyn. 2007. Factors affecting the relatie benefit of deep-banding versus broadcast application of phosphorus and potassium for corn and soybean. North Central Extension-Industry Soil Fertility Conference Proc. 23:55-63.

Bordoli, J.M., and A.P. Mallarino. 1998. Deep and shallow banding of phosphorus and potassium as alternatives to broadcast fertilization for no-till corn. Agron. J. 90:27-33.

Borges, R., and A.P. Mallarino. 1998. Variation of early growth and nutrient content of no-till corn and soybean in relation to soil phosphorus and potassium supplies. Commun. Soil Sci. Plant Anal. 29:2589-2605.

Borkert, C.M., and S.A. Barber. 1985. Predicting the most efficient phosphorus placement for soybeans. Soil Sci. Soc. Am. J. 49:901-904.

Bowman, R.A., S.R. Olsen, and F.S. Watanabe. 1978. Greenhouse evaluation of residual phosphate by four phosphorus methods in neutral and calcareous soils. Soil Sci. Soc. Am. J. 42:451-454.

Brouwer, R. 1983. Functional equilibrium: sense or nonsense? Netherlands J. Agric. Sci. 31:335-348.

Cate, R.B., and L.A. Nelson. 1965. A rapid method for correlation of soil test analysis with plant response data. Int. Soil Test Ser. Tech. Bull. 1. North Carolina State Univ. Agric. Exp. Stn., Raleigh, North Carolina.

Clarkson, D.T. 1981. Nutrient interception and transport by root systems. p. 307-314. *In*: C.B. Johnson, (ed.) Physiological processes limiting plant productivity. London: Butterworths.

Corey, R.B. 1987. Soil test procedures: Correlation. p. 15-22. *In*: J.R. Brown (ed.) Soil testing: Sampling, correlation, calibration, and interpretation. SSSA Spec. Publ. 21. SSSA, Madison, WI.

Cox, F.R. 1992. Range in soil phosphorus critical levels with time. Soil Sci. Soc. Am. J. 56:1504-1509.

Crews, T.E., K. Kitayama, J.H. Fownes, R.H. Riley, D.A. Herbert, D. Mueller-Dombosis, P.M. Vitousek. 1995. Changes in soil phosphorus fractions and ecosystem dynamics across a long chromosequence in Hawaii. Ecology. 76:1407-1424.

Dalal, R.C., and E.G. Hallsworth. 1976. Evaluation of the parameters of soil phosphorus availability factors in predicting yield response and phosphorus uptake. Soil Sci. Soc. Am. J. 40:541-545.

De Groot, C. L.F.M. Marcelis, R. Van den Boogaard, H. Lambers. 2001. Growth and dry mass partitioning in tomato as affected by phosphorus nutrition and light. Plant, Cell Environ. 24:1309-1317.

Duff, S.M.G., W.C. Plaxton, D.D. Lefebvre. 1991. Phosphate-starvation response in plant cells: *De novo* synthesis and degradation of acid phosphatases. Proc. National Academy Sci. USA. 88:9538-9542.

Dumenil, L. 1961. Nitrogen and phosphorus composition of corn leaves and corn yields in relation to critical levels and nutrient balance. Soil Sci. Soc. Am. Proc. 25:295-298.

Duncan, W.G., and A.J. Ohlrogge. 1958. Principles of nutrient uptake from fertilizer bands. II. Root development in the band. Agron. J. 50:605-608.

Eckert, D.J. 1985. Review: Effects of reduced tillage on the distribution of soil pH and nutrients in soil profiles. J. Fert. Issues. 2:86-90.

Eckert, D.J., and J.W. Johnson. 1985. Phosphorus fertilization in no-tillage corn production. Agron. J. 77:789-792.

Eghball, B., and D.H. Sandler. 1989. Distance and distribution effects of phosphorus fertilizer on corn. Soil Sci. Soc. Am. J. 53:282-287.

Ellis, B.G., C.J. Knauss, and F.W. Smith. 1956. Nutrient content of corn as related to fertilizer application and soil fertility. Agron. J. 48:455-459.

Fitter, A.H., T.R. Strickland, M.L. Harvey, and G.W. Wilson. 1991. Architectural analysis of plant root systems I: Architectural correlates of exploration efficiency. New Phytologist. 118:375-382.

Fixen, P.E., and J.H. Grove. 1990. Testing soils for phosphorus. *In*: R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, WI.

Fixen, P.E., and P.L. Carson. 1978. Relationship between soil test and small grain response to P fertilization in field experiments. Agron. J. 70:838-844.

Franzen, D.W., and T.R. Peck. 1995. Spatial variability of plant analysis phosphorus levels. Commun. Soil Sci. Plant Anal. 26:2929-2940.

Frausto da Silba, J.J.R. and R.J.P. Williams. 1991. The biological chemistry of the elements: the inorganic chemistry of life. Clarendon Press, Oxford.

Gahoonia, T.S., and N.E. Nielsen. 2004. Barley genotypes with long root hairs sustain high grain yields in low-P field. Plant Soil. 262:55-62.

Gerke, J., W. Römer, A. Jungk. 1994. The excretion of citric acid and malic acid by proteoid roots of *Lupinus albus* L.; effects on soil solution concentrations of phosphate, iron, and aluminum in the proteoid rhizosphere in samples of an oxisol and a luvisol. Zditschrift für Pflanzenernährung und Bodenkunde 157: 289-294.

Gordon, W.B. 1999. Starter fertilizers containing potassium for ridge-till corn and soybean production. Better Crops. 83:22-23.

Grahm, J.H., and D.M. Eissenstat. 1994. Host genotype and the formation of VA mycorrhizae. Plant Soil. 159:179-185.

Griffin, G.F., and R.E. Lorton. 1970. Phosphorus availability on two soils as determined by several methods. Agron. J. 62:336-341.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern corn belt. J. Soil Water Conserv. 32:22-28.

Halvorson, A.D., and A.L. Black. 1985. Long-term dryland crop responses to residual phosphorus fertilizer. Soil Sci. Soc. Am. J. 49:928-933.

Hanway, J.J., and C.R. Weber. 1971. N, P, and K percentages in soybean (*Glycine max* (L.) Merill) plant parts. Agron. J. 63:286-290.

Hanway, J.J., and R.A. Olson. 1980. Phosphate nutrition of corn, sorghum, soybeans and small grains. p. 681-692. *In*: F.E. Khasawneh et al. (ed) The role of phosphorus in agriculture. ASA, CSA, and SSSA, Madison, WI.

Hargrove, W.L. 1985. Influence of tillage on nutrient uptake and yield of corn. Agron. J. 77:763-768.

Hedley, M., and M. McLaughlin. 2005. Reactions of phosphate fertilizers and by-products in soils. p. 181-252. *In*: J.T. Sims and A.N. Sharpley (ed.) Phosphorus: Agriculture and the environment. ASA, CSA, and SSSA, Madison, WI.

Hira, G.G., and N.T. Singh. 1977. Observed and predicted rates of phosphorus diffusion in soils of varying bulk density and water content. Soil Sci. Soc. Am. J. 41:537-540.

Hodge, A. 2004. The plastic plant: root responses to heterogenous supplies of nutrients. New Phytologist. 162:9-24.

Holanda, F.S.R., D.B. Mengel, M.B. Paula, J.G. Carvaho, and J.C. Bertoni. 1998. Influence of crop rotations and tillage systems on phosphorus and potassium stratification and root distribution in the soil profile. Commun. Soil Sci. Plant Anal. 29:2383-2394.

Holford, I.C.R. 1980. Greenhouse evaluation of four phosphorus soil tests in relation to phosphate buffering and labile phosphate in soils. Soil Sci. Soc. Am. J. 44:555-559.

Howard, D.D. and D.D. Tyler. 1987. Comparison of surface applied rates of phosphorus and potassium and in-furrow fertilizer solution combinations for no-till corn production. J. Fert. Issues. 4:48-52.

Howard, D.D., M.E. Essington, and J. Logan. 2002. Long-term broadcast and banded phosphorus fertilization for corn produced using two tillage systems. Agron. J. 94:51-56.

Jacob, K.D. 1964. Predecessors of superphosphate. *In*: Superphosphate: Its history, chemistry, and manufacture. Dep. of Agric. and TVA, U.S. Gov. Print. Office, Washington, DC.

Janssen, K.A., G.M. Pierzynski, and P.L. Barnes. 1996. Phosphorus losses in runoff water as affected by tillage and phosphorus fertilization. p. 51-56. *In*: Kansas Fertilizer Research report of Progress. 778.

Jasinski, S.M. 2007. Phosphate rock. U.S. Geological survey minerals yearbook. [Online]. Available at http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/index.html#myb (verified 27 May 2008).

John, M.K., A.L. vanRyswyk, and J.L. Mason. 1967. Effect of soil order, pH, texture and organic matter on the correlation between phosphorus in alfalfa and soil test values. Can. J. Soil Sci. 47:157-161.

Johnson, A.M., D.L. Osmond, and S.C. Hodges. 2005. Predicted impacts of North Carolina's phosphorus loss assessment tool. J. Environ. Qual. 34:1801-1810.

Jones, D.L. 1998. Organic acids in the rhizosphere – a critical review. Plant Soil. 205:25-44.

Jungk, A. 2001. Root hairs and the acquisition of plant nutrients from soil. J. Plant Nutr. Soil Sci. 164:121-129.

Jungk, A., and S.A. Barber. 1975. Plant age and the phosphorus uptake characteristics of trimmed and untrimmed corn root systems. Plant Soil 42:227-239.

Kamh, M., W.J. Horst, F. Amer, J. Mostafa, and P. Maier. 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant Soil. 211:19-27.

Kamprath, E.J. 1967. Residual effect of large applications of phosphorus on high phosphorus fixing soils. Agron. J. 59:25-27.

Kamprath, E.J. 1999. Changes in phosphate availability of Ultisols with long-term cropping. Commun. Soil Sci. Plant Anal. 30:909-919.

Karathanasis, A.D., and K.L. Wells. 1990. Conservation tillage effects on the potassium status of some Kentucky soils. Soil Sci. Soc. Am. J. 54:800-806.

Karlen, D.L., E.C. Berry, T.S. Colvin, and R.S. Kanwar. 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun. Soil Sci. Plant Anal. 22:1985-2003.

Keerthisinghe, G., P. Hocking, P.R. Ryan, E. Delhaize. 1998. Effect of phosphorus supply on the formation and function of proteoid roots of white lupin (*Lupinus albus* L.). Plant Cell Environ. 21:467-478.

Ketchenson, W.J. 1980. Effect of tillage on fertilizer requirements for corn on a silt loam soil. Agron. J. 72:540-542.

Ketterings, Q.M., S. Swink, G. Godwin, K.J. Czymmek, and G.L. Albrecht. 2005. Maize silage yield and quality response to starter phosphorus fertilizer in high phosphorus soils of New York. J. Food Agric. Environ. 3:327-342.

Kissel, D.E., and J.L. Ragland. 1967. Redistribution of nutrient elements in corn (*Zea mays* L.): I. N, P, K, Ca, and Mg redistribution in the absence of nutrient accumulation after silking. Soil Sci. Soc. Am. Proc. 31:227-230.

Kovar, J.L., and S.A. Barber. Placing phosphorus and potassium for greatest recovery. J. Fert. Issues. 4:1-6.

Labhsetwas, V.K., and P.N. Soltanpour. 1985. A comparison of NH_4HCO_3-DTPA, $NaHCO_3$, $CaCl_2$, and Na_2-EDTA soil tests for phosphorus. Soil Sci. Soc. Am. J. 49:1437-1440.

Lal, R., T.J. Locan, and N.R. Fausey. 1990. Long-term tillage effect on a mollic ochraqualf in northwest Ohio. III. Soil nutrient profile. Soil Tillage Res. 15:371-382.

Lambers, H., F.S. Chapin III, and T.L. Pons. 1998. Plant physiological ecology. Springer. New York, NY.

Lathwell, D.J., N. Sanchez, D.J. Lisk, and P. Peech. 1958. Availability of soil phosphorus as determined by several chemical methods. Agron. J. 50:366-369.

Lawton, K., and J.A. Vomocil. 1954. The dissolution and migration of phosphorus from granular superphosphate in some Michigan soils. Soil Sci. Soc. Am. Proc. 18:26-32.

Lee, R.B. 1993. Control of net uptake of nutrients by regulation of influx in barley plants recovering from nutrient deficiency. Ann. Bot. 72:223-230.

Lehr, J.R., W.E. Brown, and E.H. Brown. 1959. Chemical behavior of monocalcium phosphate monohydrate in soils. Soil Sci. Soc. Am. Proc. 23:3-7.

Leikam, D.F., R.E. Lamond, and D.B. Mengel. 2003. Soil test interpretations and fertilizer recommendations. Kansas State University Agricultural Experiment Station. Department of Agronomy. MF-2568.

Linkohr, B.I., L.C. Williamson, A.H. Fitter, and H.M.O. Leyser. 2002. Nitrate and phosphate availability and distribution effects on root system architecture of *Arabidopsis*. Plant J. 29:751-760.

López-Bucio, J., M.F. Nieto-Jacobo, V. Ramírez-Rodríguez, and L. Herrera-Estrella. 2000. Organic acid metabolism in plants: from adaptive physiology to transgenic varieties for cultivation in extreme soils. Plant Sci. 160:1-13.

Luscombe, P.C., J.K. Syers, and P.E.H. Gregg. 1979. Water extraction as a soil testing procedure for phosphate. Commun. Soil Sci. Plant Anal. 10:1361-1369.

Lynch, J.P. 1995. Root architecture and plant productivity. Plant Physiol. 95:7-13.

Lynch, J.P., and K.M. Brown. 2001. Topsoil foraging – an architectural adaptation of plants to low phosphorus availability. Plant Soil. 237:225-237.

Ma, Z., D.G. Bielenberg, K.M. Brown, and J.P. Lynch. 2001. Regualtion of root hair density by phosphorus availability in *Arabidopsis thaliana*. Plant Cell Environ. 24:459-467.

MacKay, A.D., E.J. Kladivko, S.A. Barber, and D.R. Griffith. 1987. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci. Soc. Am. J. 51:970-974.

Mahtab, S.K., C.L. Godfrey, A.R. Swoboda, and G.W. Thomas. 1971. Phosphorus diffusion in soils: I. The effect of applied P, clay contant, and water content of soil. Soil Sci. Soc. Am. Proc. 35:393-397.

Mallarino, A.P., and A.M. Blackmer. 1992. Comparison of methods for determining critical concentrations of soil test phosphorus for corn. Agron. J. 84:850-856.

Mallarino, A.P. 1996. Evaluation of optimum and above optimum phosphorus supply for corn by analysis of plant parts. Agron. J. 88:376-380.

Mallarino, A.P. 1995. Evaluation of excess soil phosphorus supply for corn by the ear-leaf test. Agron. J. 87:687-691.

Matar, A.E., and M. Samman. 1975. Correlations between $NaHCO_3$-extractable P and response to P fertilization in pot tests. Agron. J. 67:616-618.

Mederski, M.J., and J.M. Wilson. 1960. Relation of soil moisture to ion absorption by corn plants. Soil Sci. Soc. Am. Proc. 35:393-397.

Mehlich, A. 1978. New extractant for soil test evaluation of phosphorus, potassium, magnesium, calcium, sodium, manganese and zinc. Commun. Soil Sci. Plant Anal. 9:477-492.

Meline, R.S., R.G. Lee, and W.C. Scott. 1972. Use of the pipe reactor in production of liquid fertilizers with very high polyphosphate content. Fertilizer Solutions. 16:32-45.

Melsted, S.W., H.L. Motto, and T.R. Peck. 1969. Critical plant nutrient composition values useful in interpreting plant analysis data. Agron. J. 61:17-20.

Mengel, D.B. 2006. Evaluating crop response to fertilizer P at different soil test P levels. Agronomy e-Updates, Kansas State University Extension (accessed at http://www.agronomy.ksu.edu/DesktopModules/ViewDocument.aspx?DocumentID=1405 on 12/04/2008).

Mengel, D.B., J.F. Moncrief, and E.E. Schulte. 1992. Fertilizer management. p. 83-87. *In*: Conservation tillage systems and Management. Midwest Plan Service, Iowa State University, Ames, IA.

Miller, .S.S., J. Liu, D.L. Allan, C.J. Menzjuber, M. Fedorova, and C.P. Vance. 2001. Molecular control of acid phosphatase secretion into the rhizosphere of proteoid roots from phosphorus-stressed white lupin. Plant Physiol. 127:594-606.

Mills, H.A., and Jones, J.B., Jr. 1996. Facotrs affecting plant composition. p. 63-111. *In*: Plant analysis handbook II. Micro Macro Publishing, Athens, GA.

Morgan, R.P.C. 1995. Soil erosion and conservation. p. 198. Longman Group Limited, Essex, U.K.

Morrison, J.E., Jr., and F.W. Chichester. 1994. Tillage system effects on soil and plant nutrient distribution on Vertisols. J. Prod. Agric. 7:364-373.

Moschler, W.W., and D.C. Martens. 1975. Nitrogen, phosphorus and potassium requirements in no-tillage and conventionally tilled corn. Soil Sci. Am. Proc. 39:886-891.

Moscheler, W.W., G.M. Shear, D.C. Martens, G.D. Jones, and R.R. Wilmouth. 1972. Comparative yield and fertilizer efficiency of no-till and conventionally tilled corn. Agron. J. 64:229-231.

Mudge, S.R., A.L. Rae, E. Diatloff, and F.W. Smith. 2002. Expression analysis suggests novel roles for members of Pht1 family of phosphate transporters in *Arabidopsis*. Plant J. 31:341-353.

Mullen, M.B., and D.D. Howard. 1992. Vertical and horizontal distribution of soil C,N,P,K, and pH in continuousno-tillage corn production. p. 6-10. *In* M.D. Mullen and B.N. Duck (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Nuruzzaman, M., H. Lambers, M.D.A. Bolland, and E.J. Veneklaas. 2005. Phosphorus uptake by grain legumes and subsequently grown wheat at different levels of residual phosphorus fertilizer. Australian J. Agric. Res. 56:1041-1047.

Nye, P.H., and P.B. Tinker. 1977. Solute movement in the soil-root system. Berkley: University of California Press.

Oko, B.F.D., and A.A. Agboola. 1974. Comparison of different phosphorus extractants in soils of the Western State of Nigeria. Agron. J. 66:639-642.

Olsen, S.R., C.V. Cole, F.S. Wanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. U.S. Gov. Print. Office, Washington, DC.

Olsen, S.R., W.D. Kemper, and J.C. van Schaik. 1965. Self diffusion coefficients of phosphorus in soil measured by transcient and steady-state methods. Soil Sci. Soc. Am. Proc. 29:154-158.

Olsen, S.R., F.S. Watanabe, and R.E. Danielson. 1961. Phosphorus absorption by corn roots as affected by moisture and phosphorus concentration. Soil Sci. Soc. Am. Proc. 25:289-294.

Onken, A.B., R. Matheson, and E.J. Williams. 1980. Evaluation of EDTA-extractable phosphorus as a soil test procedure. Soil Sci. Soc. Am. J. 44:783-786.

Pearse, S.J., E.J. Veneklaas, G. Cawthray, M.D.A. Bolland, and H. Lambers. 2006. *Triticum aestivum* shows a greater biomass response to a supply of aluminum phosphate than *Lupinus albus*, despite releasing fewer carboxylates into the rhizosphere. New Phytol. 169:515-524.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855-859.

Randall, G.W., and R.G. Hoeft. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. J. Prod. Agric. 1:70-78.

Reeves, D.W., J.T. Touchton, and C.H. Burmester. 1986. Starter fertilizer combinations and placement for conventional and no-tillage corn. J. Fert. Issues. 5:6-13.

Rehm, G.W., S.D. Evans, W.W. Nelson, and G.W. Randall. 1988. Influence of placement of phosphorus and potassium on yield of corn and soybeans. J. Fert. Issues 5:6-13.

Reichman, G.A., D.L. Grunes, C.W. Carlson, and J. Alessi. 1959. N and P composition and yield of corn as affected by fertilization. Agron. J. 51:575-578.

Richardson, S.J., D.a. Peltzer, R.B. Allen, M.S. McGlone, and R.L. Parfitt. 2004. Rapid development of phosphorus limitation in temperate rainforest along the Franz Josef soil chromosequence. Oecologia. 139:267-276.

Robbins, S.G., and R.D. Voss. 1991. Phosphorus and potassium stratification in conservation tillage systems. J. Soil Water Conserv. 46:298-300.

Robinson, D. 1991. Roots and resource fluxes in plants and communities. p. 102-130. *In*: Atkinson, D. (ed) Plant root growth: an ecological perspective. Oxford: Blackwell.

Rubio, G., T. Walk, Z. Ge, X. Yan, H. Liao, and J. Lynch. 2001. Root gravitropism and below-ground compeititon among neighboring plants: a modeling approach. Anna. Bot. 88:929-940.

Ryser, P., B. Verduyn, and J. Lambers. 1997. Phosphorus allocation and utilization in three gress species with contrasting response to N and P supply. New Phytol. 137:293-302.

Sawchik, J., and A.P. Mallarino. 2008. Variability of soil properties, early phosphorus and potassium uptake, and incidence of pests and weeks in relation to soybean grain yield. Agron. J. 100:1450-1462.

Sawyer, J. and A. Mallarino. 2007. Nutrient removal when harvesting corn stover. Integrated Crop Management. Iowa State University, Ames, IA. IC 498(22).

Schmidt, W. 2001. From faith to fate: ethylene signaling in morphogenetic responses to P and Fe deficiency. J. Plant Nutr. Soil Sci. 164:147-154.

Schünmann, P.H.D., A.E. Richardson, F.W. Smith, and E. Delhaize. 2004. Characterization of promoter expression patterns derived from the Pht1 phosphate transporter genes of barley (*Hordeum vulgare* L.). J. Exp. Bot. 55:855-865.

Schwab, G.J., D.A. Whitney, G.L. Kilgore, and D.W. Sweeney. 2006. Tillage and phosphorus management effects on crop production in soils with phosphorus stratification. Agron. J. 98:430-435.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437-451.

Sharpley, A.N., P.J.A. Kleinman, R.W. McDowell, M. Gitau, and R.B. Bryant. 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. J. Soil Water Conserv. 57:425-439.

Shear, G.M., and W.W. Moschler. 1969. Continuous corn by the no-tillage and conventional tillage method: A six year comparison. Agron. J. 61:524-526.

Singh, T.A., G.W. Thomas, W.W. Moschler, and D.C. Martens. 1966. Phosphorus uptake by corn (*Zea mays* L.) under no-tillage and conventional practices. Agron. J. 58:147-149.

Skudra, I., and A. Skudra. 2004. Phosphorus concentration in soil and winter wheat plants. Fourth International Crop Sci. Congress Proc. 2.5.4.

Sleight, D.M., D.H. Sandler, and G.A. Peterson. 1984. Effect of fertilizer phosphorus placement on the availability of phosphorus. Soil Sci. Soc. Am. J. 48:336-340.

Smethurst, P.J., and N.B. Comerford. 1993. Simulating nutrient uptake by single or competing and contrasting root systems. Soil Sci. Soc. Am. J. 57:1361-1367.

Smith, F.W., S.R. Mudge, A.L. Rae, and D. Glassop. 2003. Phosphate transport in plants. Plant Soil. 248:71-83.

Steingrobe, B. 2001. Root renewal of sugar beet as a mechanism or P uptake efficiency. J. Plant Nutr. Soil Sci. 164:533-539.

Stone, L.R., and A.J. Schlegel. 2006a. Yield –water supply relationships of grain sorghum and winter wheat. Agron. J. 98:1359-1366.

Stone, L.R., A.J. Schlegel, A.H. Khan, N.L. Klocke, and R.M. Aiken. 2006b. Water supply: yield relationships developed for study of water management. J. Nat. Resour. Life Sci. Educ. 35:161-173.

Sutton, P.J., G.S. Peterson, and D.H. Sandler. 1983. Dry matter production in tops and roots of winter wheat as affected by phosphorus availability during various growth stages. Agron. J. 75:657-663.

Thomas, G.W., and W.W. Frye. 1984. Fertilization and liming. p. 87-126. *In*: R.E. Phillips and S.H. Phillips (ed.) No-tillage agriculture principles and practices. Van Nostrand Reinhold, New York.

Thompson, L.F., and P.F. Pratt. 1954. Solubility of phosphorus in chemical extractants as indexes to available phosphorus in Ohio soils. Soil Sci. Soc. Proc. 18:467-470.

Toler, J.E., E.C. Murdock, and J.J. Camberato. 2004. Starter fertilizer effects on cotton development and weed interference. J. Cotton Sci. 8:33-41.

Touchton, J.T., and D.H. Rickerl. 1986. Soybean growth and yield resonses to starter fertilizer. Soil Sci. Soc. Am. J. 50:234-237.

Turner, F.T., and J.W. Gilliam. 1976. Increased P diffusion as an explanation of increased P availability in flooded rice soil. Plant Soil. 45:365-377.

Tyler, D.D., and D.D. Howard. 1991. Soil sampling patterns for assessing no-tillage fertilization techniques. J. Fert. Issues. 8:52-56.

Tyner, E.H. 1947. The relation of corn yields to leaf nitrogen phosphorus and potassium content. Soil Sci. Soc. Am. Proc. 11:317-323.

Ulrich, A., and F.J. Hills. Principles and practices of plant analysis. p. 11-24. *In*: G.W. Hardy (ed.) Soil testing and plant analysis. Part 2. Soil Sci. Soc. Am. Spec. Pub. 2. Soil Sci. Soc. Am., Madison, WI.

van Buren, N. 1979. 25 years of progress culminates in St. Louis. Fertilizer Solutions 23:8-18, 30-34.

Vance, C.P., C. Whde-Stone, and D.L. Allan. 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol. 157:423-447.

Vanderlip, R.L. 1993. How a sorghum plant develops. Kansas State University Agricultural Experiment Station, Department of Agronomy, Contribution No. 1203.

van Diest, A. 1963. Soil test correlation studies on New Jersey soils: 1. Comparison of seven methods for measuring labile inorganic soil phosphorus. Soil Sci. 96:261-266.

Van Raij, B., J.A. Quaggio, and N.M. da Silva. 1986. Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion exchange resin procedure. Commun. Soil Sci. Plant Anal. 17:547-566.

Viets, F.G., C.E. Nelson, and C.L. Crawford. 1954. The relationship among corn yields, leaf composition and fertilizers applied. Soil Sci. Soc. Am. Proc. 18:297-301.

Walker, T.C., and J.K. Syers. 1976. The fate of phosphorus during pedogenesis. Geoderma 15:1-19.

Walter, W.M., and T.R. Peck. 1975. Relationship between corn yield and plant potassium. Agron. J. 67:445-448.

Welch, L.F., D.L. Mulvaney, L.V. Boone, G.E. McKibben, and J.W. Pendleton. 1965. Relative efficiency of broadcast versus banded phosphorus for corn. Agron. J. 58:283-287.

Wendt, R.C., and R.B. Corey. 1981. Available P determination by equilibrium with dilute $SrCl_2$. Commun. Soil Sci. Plant Anal. 12:557-568.

Williams, C.H. 1969. Moisture uptake by surface-applied superphosphate and movement of the phosphate and sulphate into the soil. Aust. J. Soil Res. 7:307-316.

Williams, C.H. 1971. Reaction of surface-applied superphosphate with soil: II. Movement of the phosphorus and sulfur into the soil. Aust. J. Soil Res. 9:95-106.

Williams, E.G. 1966. The intensity and quality aspects of phosphate status and laboratory extraction values. Ann. Edafol. Agrobiol. 26:525-546.

Williamson, L.C., S.P.C.P. Ribrioux, A.H. Fitter, and H.M.O. Leyser. 2001. Phosphate availability regulates root system architecture in Arabidopsis. Plant Physiol. 126:875-882.

Wright, A.L., F.M. Hons, R.G. Lemon, M.L. McFarland, and R.L. Nichols. 2007. Stratification of nutrients in soil for different tillage regimes and cotton rotations. Soil Tillage Res. 96:19-27.

Yli-Hilla, M., H. Hartikainen, P. Ekholm, E. Turtola, M. Puustinenb, and K. Kallio. 1995. Assessment of soluble phosphorus load in surface runoff by soil analyses. Agric. Ecosyst. Environ. 56:53-62.

Young, R.D. and C.H. Davis. 1980. Phosphate fertilizers and process technology. p. 195-226. *In*: F.E. Khasawneh et al. (ed.) The role of phosphorus in agriculture. ASA, CSSA, and SSSAJ, Madison, WI.

Zubriske, J.C. 1971. Relationships between forms of soil phosphorus, some indexes of phosphorus availability and growth of sudangrass in greenhouse trials. Commun. Soil Sci. Plant Anal. 16:467-484.

CHAPTER 2 - Effect of Phosphorus Placement in Reduced Tillage Systems in Kansas

Abstract

No-tillage and reduced tillage systems cause significant phosphorus (P) management concerns due to P stratification, an increased P concentration at the soil surface. Two of the many factors that contribute to this problem are traditional broadcasting of P fertilizer without incorporation into the soil and P uptake by plants followed by decomposition and release of P into the surface of the soil. Using a deep band fertilization method has been considered a way to reduce the effects of stratification by placing the P fertilizer deeper in the soil. The level of response from deep banding is likely influenced by the severity of existing stratification, initial soil test P levels, and rainfall patterns. The objectives of this study are to: 1) determine if P availability to crops is limited by stratification, 2) determine the role precipitation, irrigation and soil moisture play in the availability of soil P and fertilizer P, and 3) evaluate how P fertilizer rate and placement (deep band and broadcast) impact P availability. This study was conducted at four sites across Kansas ranging from 440 to 1000 mm mean annual precipitation. Crops in this study included corn, soybean, sorghum, and wheat. Phosphorus fertilizer was applied as broadcast, deep band, and combinations of each with starter. Each site had known P stratification prior to the initiation of the study, with soil test P concentrations of 9.4 to 74.1 mg kg^{-1} in the 0 to 7.6 cm soil layer. Two of the sites had low soil test P (Scandia and Ottawa) and were responsive to P fertilization. However, a consistent effect due to P placement on yield or nutrient uptake was not seen at these sites. At Scandia (a high yield potential, low P availability site), direct application of P on soybean was important in achieving optimum yields. The high soil test P sites (Manhattan and Tribune) did not consistently respond to P fertilization. Data from this study showed that P stratified soil does not negatively affect crop yields and when a crop response was observed, the P application rate was much lower than the recommended rate.

The effect of soil moisture appeared to have little effect on crop responses. This work, conducted in a more arid climate, provides needed information to complement previous studies done in more humid environments.

Introduction

Phosphorus management of no-tillage and reduced tillage crop production, particularly sub-surface application techniques, has been studied in recent years because these tillage practices lead to surface P stratification. Nutrient stratification refers to the non-uniform distribution of nutrients within the soil in relation to depth, where higher concentrations of the nutrient are found near the soil surface. Concerns related to stratification include potential impact on crop yield and nutrient uptake due to inability of the crops to access nutrients (Mallarino and Borges, 2006). In no-tillage systems, P stratification is the result of surface application (Eckert, 1985; Tyler and Howard, 1991; Morrison and Chichester, 1994; Mullen and Howard, 1992) and decreased mixing of the fertilizer applied on the soil surface with deeper soil (Griffith et al., 1977; MacKay et al., 1987; Karlen et al., 1991; Robbins and Voss, 1991). Several authors have noted that P stratification is also a result of plants taking up P and releasing the P on the soil surface after decomposition of crop residue (Shear and Moschler, 1969; Griffith et al., 1977; Ketchenson, 1980; Mackay et al., 1987; Karathanasis and Wells, 1990; Karlen et al., 1991).

Although it is known that crop responses to P application are common on low P soil regardless of placement (Bordoli and Mallarino, 1998; Eckert and Johnson, 1985; Rehm et al., 1988), research has targeted P application methods as a way to improve crop yields. Probably the most consistent P response in no-till soils is to starter (5 cm to the side and 5 cm below the seed) applied fertilizer on low P soil, as described by Randall and Hoeft (1998). Broadcast application also has positive response in no-till systems with low soil test P (Bordoli and Mallarino, 1991). High P soils in no-till corn systems have also shown yield responses when P was applied as a broadcast (Mallarino, 1991) or starter application (Gordon et al., 1997). An Iowa study on soybean showed deep placed P responded similar to broadcast applied P and the general outcome was that deep placement didn't increase yields as compared to broadcasting, but there was no decrease in yield if deep application was done for other agronomic reasons (Bordoli and Mallarino, 2000). Some research has shown surface broadcast application to be as effective or superior to incorporated or band applied P in no-till corn production (Moscheler et al., 1972; Howard and Tyler, 1987), but Southeast Kansas research showed increased P uptake and grain yield when P was applied below the soil surface in corn and sorghum production (Schwab et al., 2006). The effectiveness of residual band and broadcast incorporated (by tillage) P showed that although P recovery was highest with band applied P, broadcast applied P also resulted in increased yields (Barber, 1980).

Although conflicting research exists on which application placement is superior, many factors must be considered when determining which method to use. The amount of soil that comes in contact with P fertilizer from broadcast, band, and starter application varies widely. Band and starter fertilization techniques apply P in a more concentrated zone, thus contacting less of the bulk soil. While this results in a higher available P concentration in the treated zone, Borkert and Barber (1985) showed that with a high application rate, the volume of soil that needs to be in contact with the P fertilizer also increases in order to maximize P uptake. Kovar and Barber (1987) demonstrated that the greatest P recovery occurred when at least 5% of the soil volume was fertilized. Because of this, optimum placement becomes vital when soil test P and fertilizer rates are low.

Phosphorus placement is also important in moisture limiting environments because root access to P is dependant on the depth of moisture. Toler et al. (2004) found that the response to P on high soil test P sites is highly dependant on soil moisture. This moisture is integral for P uptake (Mederski and Wilson, 1960; Olsen et al., 1961) due to its influence on P diffusion through the soil to the plant roots (Olsen et al., 1965; Mahtab et al., 1971; Hira and Singh, 1977). However, the diffusion rate of P is less affected by soil moisture at high soil test P levels than low because the diffusion rate is driven by the amount of P in the soil solution (Mahtab et al., 1971).

The effects of nutrient stratification have been studied in humid environments and resulted in small, sporadic reductions in nutrient availability (Belcher and Ragland, 1972; Moschler and Martens, 1975). These findings have not been supported by research conducted in more arid climates. Since moisture is a vital component in P uptake, but a factor limiting crop production in the western Great Plains, it is a primary concern in this study.

To date, the study by Schwab et al. (2006) was the only P management study which considered fertilizer placement in stratified soil in Kansas. Howard et al. (2002) identified several conditions important for P management for crop production in long-term no-till systems that impact nutrient availability. These include band applied P for periods of drought, fertilization rate, soil test level, and soil texture. All these factors are primary concerns for crop production in Kansas, but most specifically is the concern for drought or low soil moisture conditions that have not been studied to reflect common field conditions across Kansas.

The objectives of this study are to: 1) determine if P availability to crops is limited by stratification, 2) determine the role precipitation, irrigation and soil moisture play in the availability of soil P and fertilizer P, and 3) evaluate how P fertilizer rate and placement (deep band and broadcast) impact P availability.

Materials and Methods

Four sites were established in the spring of 2005. The Scandia site is located west of Scandia, KS on the North Central Agronomy Experiment Field (39°46′23″ N lat.; 97°47′19″ W long.). The soil is classified as a Crete silt loam (fine, smectitic, mesic Pachic Argiustolls). The Ottawa site is located south of Ottawa, KS on the East Central Agronomy Experiment field (38°32′19″ N lat.; 95°15′11″ W long.) and the soil is classified as a Woodson silt loam (fine, montmorillonitic, thermic, Abruptic Argiaquoll). The Manhattan site is located in Manhattan, KS on the Agronomy North Farm (39°08′02″ N lat.; 96°37′09″ W long.). The soil at this site is classified as a Smolan silt loam (fine, smectitic, mesic Pachic Argiustolls). The Tribune site is located west of Tribune, KS on the Southwest Research and Extension Center (38°28′03″ N lat.; 101°46′03″ W long.), and the soil is classified as a Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls). The 30-year mean annual rainfall totals for these sites are 440 mm. 710 mm, 810 mm and 1000 mm for Tribune, Scandia, Manhattan, and Ottawa, respectively (http://countrystudies.us, accessed 8/2008). All sites were rainfed except Scandia, which received supplemental irrigation. Each site except Tribune had a history of no-till production practices for greater than 5 years and thus P stratification was expected to exist.

Common crop rotations for the region were used at each location with each crop present in each year. Rotations used were Corn-Soybean at Ottawa and Scandia, Sorghum-Soybean-Wheat at Manhattan and Wheat-Sorghum-Fallow at Tribune. Planting dates, harvest dates, crop, and populations are summarized in Table 2.1.

Table 2.1 Location, year, crop, planting date, seeding rate, and harvest date for all sites in all years.

Location	Year	Crop	Planting date	Seeding rate (seeds ha^{-1})†	Harvest Date
Scandia	2006	Corn	4/20/2006	76100	10/3/2006
	2006	Soybean	5/17/2006	395300	10/12/2006
	2007	Corn	5/16/2007	89000	10/10/2007
	2007	Soybean	6/4/2007	395300	10/9/2007
	2008	Corn	5/2/2008	86500	10/27/2008
	2008	Soybean	5/16/2008	395300	10/10/2008
Ottawa	2006	Corn	4/7/2006	61800	9/7/2006
	2006	Soybean	5/22/2006	296500	10/13/2006
	2007	Corn	5/19/2007	68000	9/20/2007
	2007	Soybean	5/23/2007	2965000	10/24/2007
	2008	Corn	5/14/2008	68000	9/29/2008
	2008	Soybean	5/21/2008	345900	10/20/2008
Manhattan	2005-06	Winter Wheat	10/31/2005	135 kg ha^{-1}	6/21/2006
	2006	Sorghum	5/19/2006	177900	10/13/2006
	2006	Soybean	5/18/2006	292000	10/23/2006
	2006-07	Winter Wheat	10/30/2006	130 kg ha^{-1}	7/5/2007
	2007	Sorghum	5/18/2007	168000	10/18/2007
	2007	Soybean	5/18/2007	303900	10/22/2007
	2007-08	Winter Wheat	10/25/2007	130 kg ha^{-1}	6/26/2008
	2008	Sorghum	5/19/2008	148700	9/19/2008
	2008	Soybean	5/16/2008	257500	10/5/2008
Tribune	2005-06	Winter Wheat	10/27/2005	135 kg ha^{-1}	6/26/2006
	2006	Sorghum	6/5/2006	81600	11/9/2006
	2006	Fallow	-	-	-
	2006-07	Winter Wheat	10/12/2006	100 kg ha^{-1}	6/27/2007
	2007	Sorghum	5/31/2007	81600	11/1/2007
	2007	Fallow	-	-	-
	2007-08	Winter Wheat	10/4/2007	100 kg ha^{-1}	7/9/2008
	2008	Sorghum	6/7/2008	81600	11/6/2008
	2008	Fallow	-	-	-

†= kg ha^{-1} seeding rate in wheat

Kansas farmers routinely use multiyear fertilization practices for P, focusing on fertilization of corn, sorghum, and wheat. Soybean is not routinely fertilized because they are expected to receive residual P fertilizer not utilized by the previous crop. In this study, that practice was also followed with corn and soybean commonly being grown in rotation and most P being applied to the corn with soybeans relying heavily on residual fertility. At Manhattan and Tribune, P fertilizers were applied to both sorghum and wheat, with no P applied to soybeans at Manhattan. Two additional treatments were designed specifically to determine if this rotational fertilization system was appropriate, and if soybean would respond to additional direct P applications. The twelve treatments included:

1) 0 kg P ha^{-1} (CHECK)
2) 8.7 kg P ha^{-1} starter (ST)
3) 17.4 kg P ha^{-1} broadcast (LOW BDCST)
4) 8.7 kg P ha^{-1} starter and 8.7 kg P ha^{-1} broadcast (LOW BDCST+ST)
5) 17.4 kg P ha^{-1} deep band (LOW BND)
6) 8.7 kg P ha^{-1} starter with 8.7 kg P ha^{-1} deep band (LOW BND+ST)
7) 34.8 kg P ha^{-1} broadcast (HI BDCST)
8) 8.7 kg P ha^{-1} starter and 26.1 kg P ha^{-1} broadcast (HI BDCST+ST)
9) 34.8 kg P ha^{-1} deep band (HI BND)
10) 8.7 kg P ha^{-1} starter and 26.1 kg P ha^{-1} deep band (HI BND+ST)
11) 8.7 kg P ha^{-1} starter and 26.1 kg P ha^{-1} broadcast with 17.4 kg P ha^{-1} broadcast on soybean (HI BDCST+ST+SOY)
12) 8.7 kg P ha^{-1} starter and 26.1 kg P ha^{-1} deep band with 17.4 kg P ha^{-1} broadcast on soybean. (HI BND+ST+SOY)

A randomized complete block design was used at each site with three replications at Manhattan and four replications at all other sites. Since soybeans were not included in the rotation at Tribune, treatments 11 and 12 were not included for Tribune. Starter P was applied 5 cm to the side and 5 cm below the seed on row planted crops (corn and sorghum) at Scandia, Ottawa, and Manhattan and was applied with the seed in drilled crops (winter wheat) and sorghum at Tribune. Broadcast application was always applied on the soil surface just prior to planting with a drop-type spreader or hand-applied. Deep band treatments were applied with a strip till unit at approximately 15 cm deep in row crops (except sorghum at Tribune). In winter wheat, a coulter applicator on 38 cm spacing was used to apply the P as deep as possible (~10 cm). Due to moisture limited conditions and excessive soil drying from strip till operations, deep application of P at Tribune after the first year was accomplished using a coulter applicator for all crops. When fertilizer was deep banded via strip tillage, all treatments of the crop were strip tilled (even if fertilizer was not applied) to eliminate any tillage effects on study results. Corn and sorghum crops were strip tilled, while wheat and soybean were no-tilled. Forms of P fertilizer used were ammonium polyphosphate (10-34-0) or triple superphosphate (0-46-0). Appropriate nitrogen application rates were used and balanced so all treatments received the same nitrogen rates at each location and thus effects due to nitrogen were eliminated. Initial soil test P data was taken at the onset of this study by collecting one composite sample (by depth) for each replication at all sites (Table 2.2).

Plant tissue samples were taken during the vegetative and reproductive portion of the growth cycle of most crops, years, and locations. Some vegetative samples were not taken due to environmental or climatic stresses that created uncertainty in the data or if the target growth stage for plant sampling was missed, which has been noted in the data tables. During the early vegetative growth, samples were taken at the V6 stage (six leaf collars present) for corn, V4 stage (trifoliate leaves at four nodes) for soybean, GS2 for sorghum , and Feekes 6 growth stage for wheat. This was accomplished by removing 15 corn plants at random from both border rows of each plot. For soybean, grain sorghum, and wheat, two sections of a row 91.5 cm long were cut from each plot. Plants were weighed and dried in a forced air oven at 60°C for a minimum of 4 days and weighed for biomass calculation. Once dry, the plants were ground with a Wiley grinder, digested using a sulfuric acid and hydrogen peroxide digest (Thomas et al., 1967) and colormetrically analyzed for total P content with a 300 series Alpkem Rapid Flow Analyzer. The biomass weight and P concentration was used to calculate P uptake.

Standard tissue samples for nutrient analysis near the end of vegetative growth were collected at the growth stages appropriate for each crop in the study. These were: ear leaf in corn during silking, uppermost trifoliates without the petiole in soybean during pod formation, and flag leaves in grain sorghum and at half bloom in wheat. Fifteen leaves were sampled from the border rows of each plot in corn and sorghum and 30 leaves were sampled in soybean and wheat plots. Grinding and analysis followed the same procedure as earlier plant samples, but samples were not weighed.

The center 152 cm width of each plot was machine harvested or hand harvested (at Manhattan in 2006 and 2008 in grain sorghum). Grain weight was recorded and adjusted for 155, 130, 125, and 125 g kg $^{-1}$ moisture for corn, soybean, sorghum, and wheat, respectively. Grain was dried at 60°C for a minimum of four days, ground to a powder and digested with a sulfuric acid and hydrogen peroxide digest (Thomas et al., 1967). Samples were then analyzed as previously described for leaf samples.

Statistical Analysis

Data was analyzed by location using years as a random variable unless otherwise stated (due to application totals for the rotation). Each crop at each location was first analyzed using *proc mixed* (SAS, 2007) to determine if there was a response to P treatments. When soybeans were evaluated, there was no previous P application in 2006 as this was the first crop year, and therefore this was viewed as a 'setup' year for the rotation. Because of this, analysis did not include 2006 soybean data. The P responsive parameters/measurements were regressed to describe the effect of P application rate. The models evaluated include linear plateau, quadratic plateau (both analyzed using *proc nlmixed*, SAS, 2007), linear, and quadratic (both analyzed using *proc reg*, SAS, 2007). If there was a response to P, a two by two by two factorial analysis was conducted on starter by placement by rate. This evaluated starter, no starter, broadcast, and deep band applied P, 17.4 kg P ha^{-1} and 34.8 kg P ha^{-1} rates and the interaction of any or all factors. Mean values were reported for the comparison of main effects and interactions were graphically displayed with letters indicating significant differences. The level of alpha was held at 0.10 for any data display where mean separation was indicated using letters.

Results and Discussion

Initial soil test P levels, determined at the onset of this experiment (2005) are summarized in Table 2.2. Two sites, Ottawa and Scandia, had surface (0-7.6 cm) P concentrations in the very low range, while Manhattan and Tribune were in the very high range (Leikam et al., 2003). The next sampling depth (7.6-15 cm) showed that P concentration decreased dramatically, which confirmed P stratification. Ottawa and Scandia are the only sites that would be expected to be responsive to P fertilizer.

Table 2.2 Initial mean soil test P content for each site by depth.

	Scandia	Ottawa	Manhattan	Tribune
Depth (cm)	---P (mg kg^{-1})---			
0-7.6	9.5	9.4	55.4	74.1
7.6-15	5.7	5.8	19.9	31.3
15-23	5.1	4.8	7.0	10.3
23-31	5.4	4.7	4.2	13.4
31-61	4.6	4.6	3.4	23.5

Scandia

Corn

The Scandia corn was the most responsive site/crop combination in this study. The data collected is summarized in Table 2.3 and shows the response of corn over the course of the growing season to applied P over the three years of the study (Treatments 1-10 only). A statistically significant response to applied P was seen in all the parameters measured.

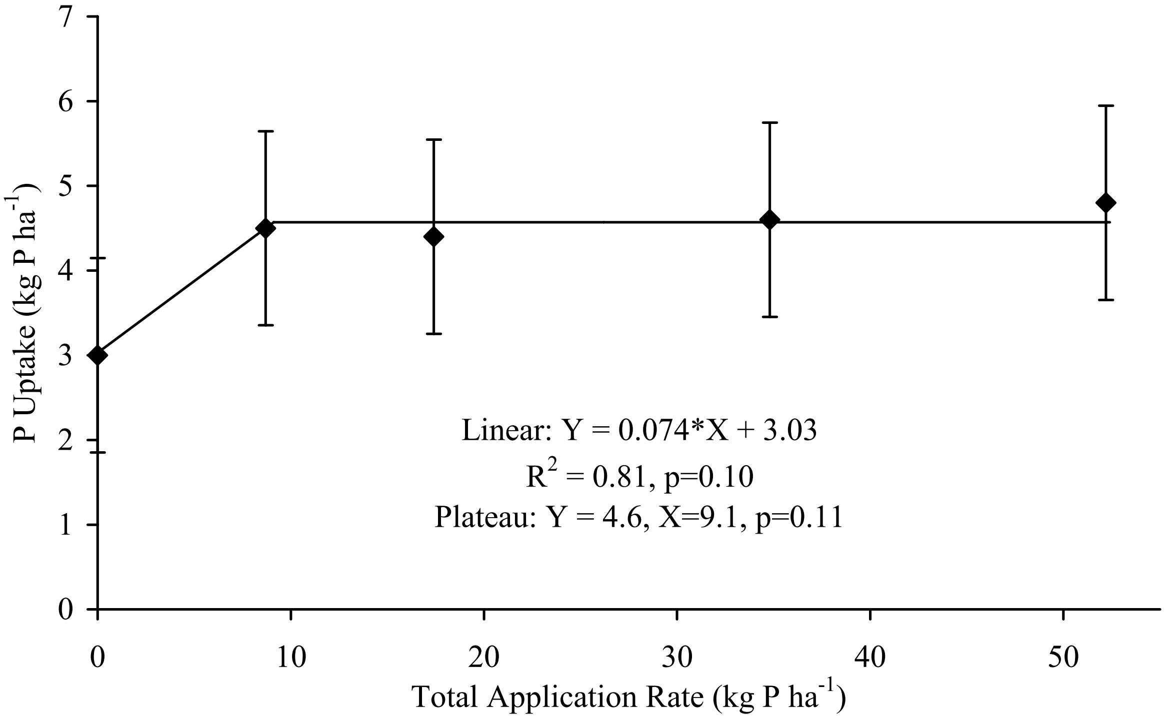
Table 2.3 Effect of phosphorus treatments on corn plant and grain P concentration and yield at Scandia in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	------------Whole Plant (V6)------------			---Leaf†---	-----------Grain-----------	
(kg P ha^{-1})	P Conc. ‡ (g kg^{-1})	Biomass‡ (kg ha^{-1})	P Uptake‡ (kg P ha^{-1})	P Conc. (g kg^{-1})	P Conc. (g kg^{-1})	Yield (kg ha^{-1})
CHECK	3.1 d	960 d	3.0 f	2.1 d	2.4 de	9390 c
ST	3.5 c	1290 ab	4.5 cd	2.5 bc	2.5 abcde	10800 ab
LOW BDCST	3.6 c	1050 d	3.9 e	2.5 b	2.4 e	10700 b
LOW BDCST+ST	3.7 c	1210 bc	4.4 cde	2.5 bc	2.5 bcde	11120 a
LOW BND	3.8 abc	1210 bc	4.6 c	2.5 bc	2.4 e	10960 ab
LOW BND+ST	3.7 c	1300 ab	4.7 bc	2.5 c	2.4 cde	10950 ab
HI BDCST	4.0 ab	1300 ab	5.3 ab	2.6 ab	2.6 a	10800 ab
HI BDCST+ST	3.8 bc	1210 bc	4.6 c	2.7 a	2.6 abc	11000 ab
HI BND	3.7 c	1100 cd	3.9 de	2.4 c	2.6 ab	10930 ab
HI BND+ST	4.1 a	1400 a	5.7 a	2.6 ab	2.6 abcd	11090 a
Pr > F	<0.01	<0.01	<0.01	<0.01	0.06	<0.01

Letters indicate significant differences at alpla ≤ 0.10
† = ear leaf
‡ = samples not collected in 2006

To examine the effect of total P applied to the rotation of corn and soybean on corn growth and development, a regression of P applied, consisting of the CHECK, ST, LOW BDCST+ST, HI BDCST+ST, HI BDCST+ST+SOY treatments was done. The early season response to increasing rate of P, as measured by plant uptake, is shown in Figure 2.1. A significant increase in P uptake was obtained from the first increment of P applied as starter, with no additional response obtained to higher rates, including the residual impact of P applied to rotational soybeans. A linear plateau model was found to best describe this data.

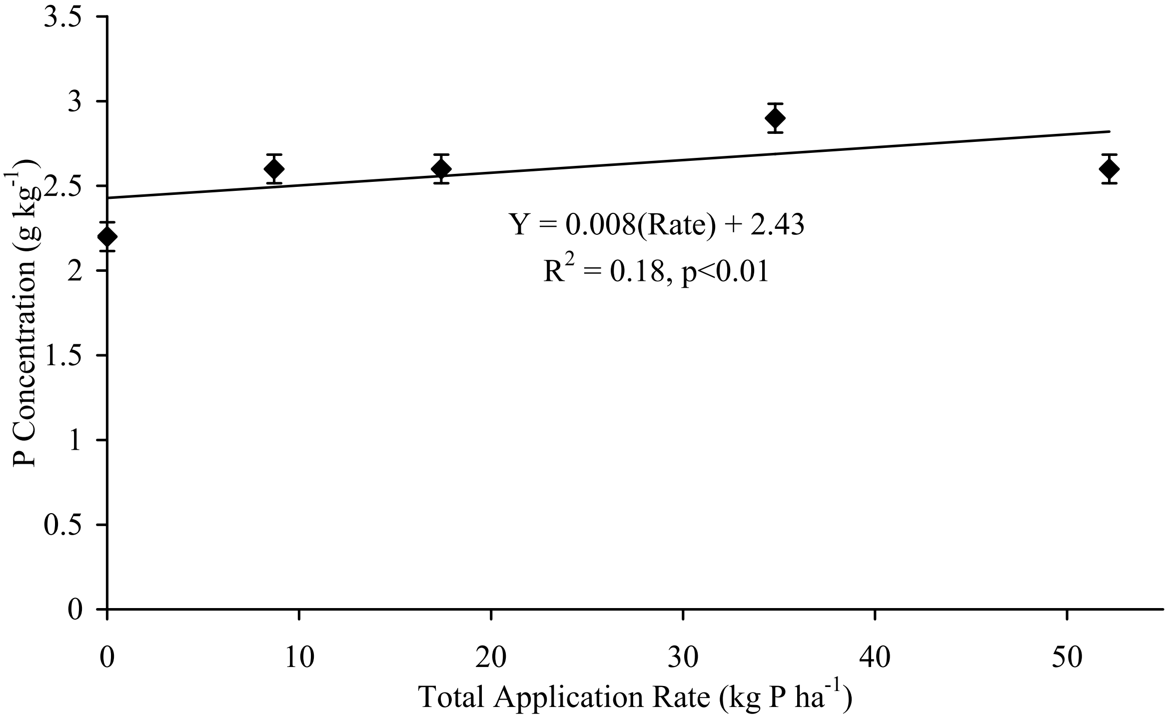
Figure 2.1 Effect of Phosphorus fertilizer application on corn P uptake at V6 response at Scandia (mean data for 2007 and 2008).



Linear plateau model fit using *proc nlmixed* (SAS, 2007)
Error bars represent the standard error of the means.
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

A similar regression was conducted to describe the effects of increasing P application of the earleaf P concentration at silking, a common plant diagnostic used to measure P sufficiency in corn (Figure 2.2). While a significant linear increase in corn ear leaf P concentration with increasing P application was observed, the rate response model was a poor fit with a low slope (0.008), indicating that ear leaf P concentration was not highly responsive across the rates evaluated. Since the commonly accepted critical level 2.5 g P kg^{-1} was met by the all the treatments except the check, this is not surprising.

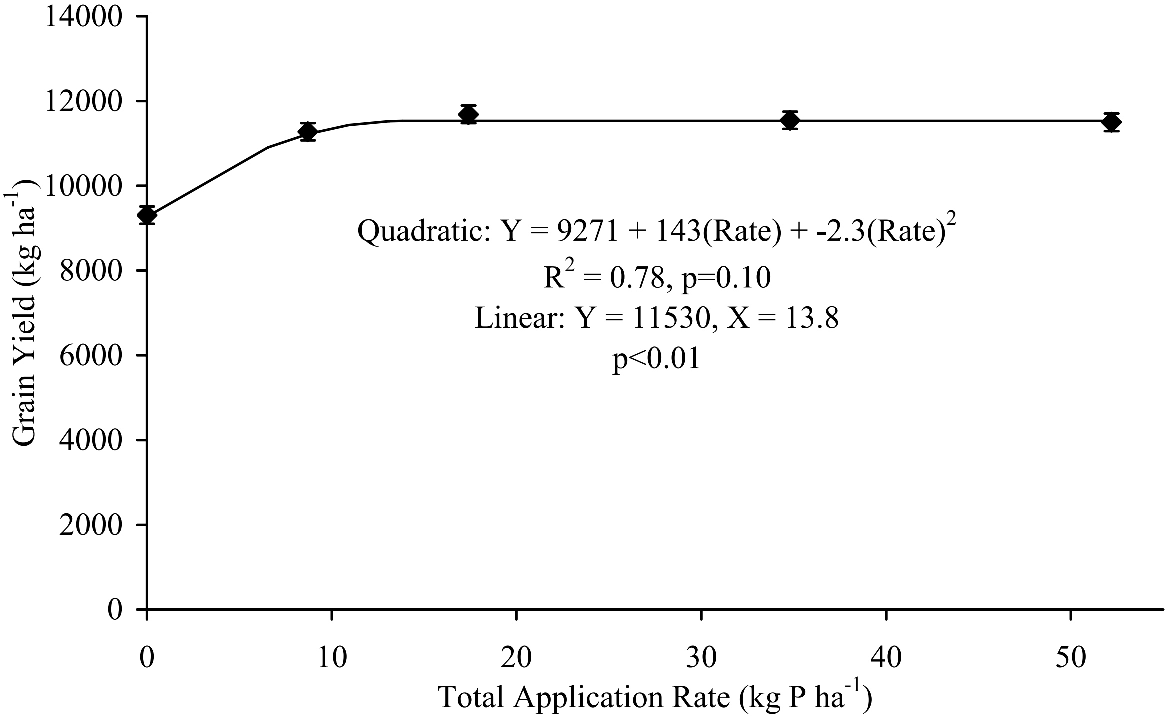
Figure 2.2 Phosphorus fertilizer application and corn ear leaf P concentration response at Scandia (mean data for 2007 and 2008).



Linear model fit using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

The quadratic plateau model in Figure 2.3 defines the response in grain yield found at this site. The plateau point was found at an application rate of 13.8 kg P ha^{-1}, between the two lowest rates of application. Although responses were expected at rates up to 20 kg P ha^{-1}, P application greater than 13.8 kg P ha^{-1} did not increase yields above 11,530 kg ha^{-1}.

Figure 2.3 Phosphorus fertilizer application and corn grain yield response at Scandia in 2007 and 2008.



Quadratic plateau model fit using *proc nlmixed* (SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

A 2x2x2 factorial analysis of the response of corn to starter fertilizer, P application method, and P application rate was conducted to further explain the response to P and help explain how these variables interact. The results of this analysis are reported in Table 2.4.

Table 2.4 Factorial analysis of starter fertilizer, placement, and P rate in corn at Scandia in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

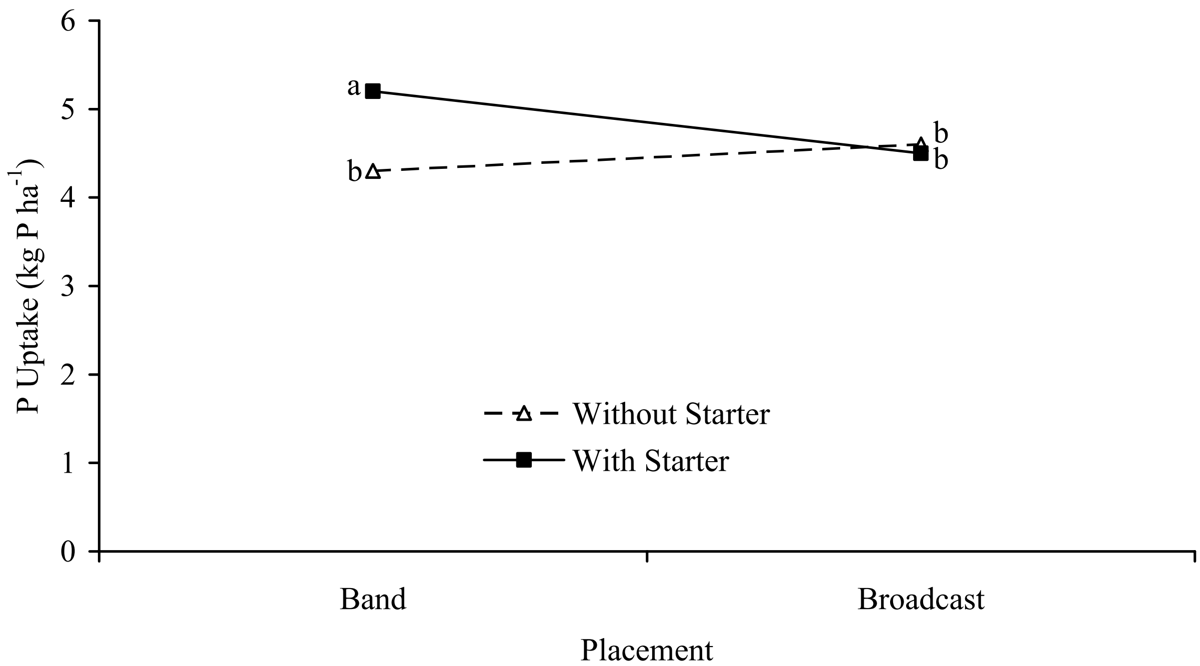
	------------Whole Plant (V6)------------			---Leaf†---	-----------Grain-----------	
Effect	P Conc. ‡	Biomass‡	P Uptake‡	P Conc.	P Conc.	Yield
	(g kg^{-1})	(kg ha^{-1})	(kg P ha^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
Starter (kg P ha^{-1})						
0	3.8	1170	4.4	2.5	2.5	10850
8.7	3.8	1280	4.8	2.6	2.5	11040
Placement						
Band	3.8	1250	4.7	2.5	2.5	10980
Broadcast	3.8	1190	4.5	2.6	2.5	10910
Rate (kg P ha^{-1})						
17.4	3.7	1190	4.4	2.5	2.4	10930
34.8	3.9	1250	4.9	2.6	2.6	10960
F significance						
Starter	0.76	0.02	0.03	0.04	0.71	0.01
Placement	0.67	0.22	0.25	0.06	0.63	0.31
Rate	0.04	0.18	0.02	0.16	<0.01	0.75
Starter × Placement	0.15	0.08	<0.01	0.22	0.90	0.11
Starter × Rate	0.59	0.81	0.62	0.11	0.27	0.83
Placement × Rate	0.52	0.16	0.08	0.11	0.92	0.66
Starter × Placement × Rate	0.03	0.01	<0.01	0.78	0.88	0.18

† = ear leaf
‡ = samples not collected in 2006

It is clear from the main effects of the treatment factors that early season P uptake significantly increased when starter was applied and when the overall P rates increased from 17.4 kg P ha^{-1} to 34.8 kg P ha^{-1} (Table 2.4). However, no difference in early season P uptake was observed between broadcast or band applications of P. At mid season, significant effects of starter and P placement on corn earleaf P concentration were observed with greater P concentration with starter fertilizer and broadcast application. At harvest, a significant response to starter fertilizer was seen on grain yield. However, no effects of P placement or rate above the 17.4 kg ha^{-1} rate were observed on grain yields.

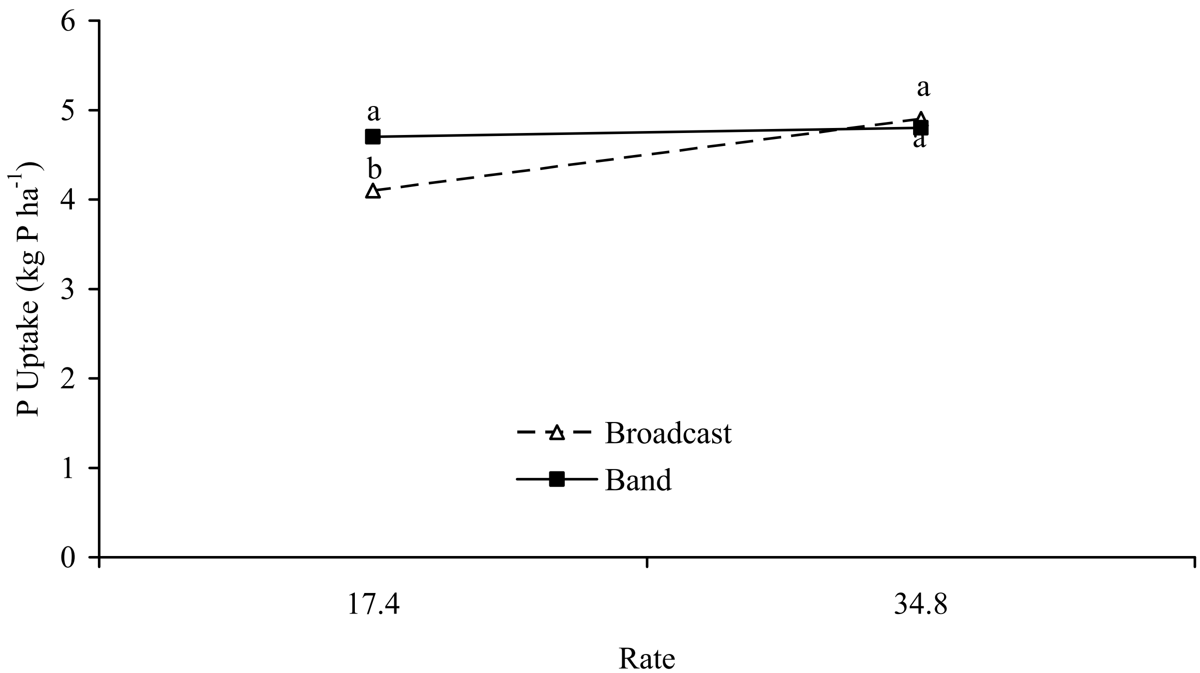
There were significant starter by placement and placement by rate interactions on early season P uptake, as shown in Figures 2.4 and 2.5. No interactions of the three factors were seen at later stages of growth.

Figure 2.4 Interaction of starter and placement of fertilizer on corn P uptake at the V6 stage at Scandia in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).



Letters indicate significant differences at alpha=0.10

Figure 2.5 Interaction of placement and rate of fertilizer on corn P uptake at the V6 stage at Scandia in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).



Letters indicate significant differences at alpha=0.10

The interaction of starter by placement showed increased P uptake when starter was used with a deep band application of P, (Figure 2.4), but not when starter was applied with broadcast applications of P. This is likely due to the deep banded P being below the reach of the seedling root during the earliest phases of growth. During this time, the surface broadcast P was readily available to the seedlings. The placement by rate interaction showed an advantage to banding P on early uptake at low rates but not broadcasting at low rates (Figure 2.5).

Soybean

The effects of residual P applied to corn and direct fertilization with P on soybean are reported in Table 2.5. In general, responses were seen, especially to the higher residual rates and direct application of P on yield and some vegetative measurements.

Table 2.5 Effect of phosphorus treatments on soybean plant and grain P concentration and yield at Scandia in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	------------Whole Plant (V4)------------			---Leaf†---	-----------Grain-----------	
(kg P ha^{-1})	P Conc. ‡	Biomass‡	P Uptake‡	P Conc.	P Conc.	Yield
	(g kg^{-1})	(kg ha^{-1})	(kg P ha^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	2.8 e	760	2.1	2.7 ef	4.5 bc	3020 d
ST	3.0 cde	810	2.4	2.9 bcde	4.5 bc	3250 c
LOW BDCST	3.0 cde	770	2.3	2.8 def	4.6 bc	3310 bc
LOW BDCST+ST	3.1 abc	760	2.4	3.0 ab	4.6 bc	3250 c
LOW BND	2.9 de	800	2.3	2.8 def	4.5 c	3310 bc
LOW BND+ST	3.2 ab	750	2.4	2.7 f	4.7 abc	3250 c
HI BDCST	3.0 bcd	790	2.4	2.8 def	4.8 ab	3340 bc
HI BDCST+ST	3.2 ab	710	2.3	2.8 cdef	4.9 a	3330 bc
HI BND	3.0 bcd	760	2.3	2.8 ef	4.8 ab	3350 bc
HI BND+ST	3.2 a	770	2.5	3.0 abc	4.9 a	3300 bc
HI BDCST+ST+SOY	3.2 ab	720	2.3	3.1 a	4.9 a	3400 b
HI BDCST+ST+SOY	3.1 abc	730	2.2	3.0 bcd	4.9 a	3630 a
Pr > F	<0.01	0.76	0.81	<0.01	0.05	<0.01

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = uppermost trifoliates without the petioles during pod formation
‡ = samples not collected in 2007

A more direct comparison of residual and direct fertilization of the soybean at Scandia is given in Table 2.6. In these comparisons, the CHECK, residual effects from HI BDCST+ST and HI BND+ST, and the direct effects of HI BDCST+ST+SOY and HI BND+ST+SOY were evaluated. The HI BDCST+ST treatment represents the P application program typical of most Kansas farmers. Both treatments with SOY include the residual application identical to HI BDCST+ST and HI BND+ST plus the direct broadcast P application of 17.4 kg P ha^{-1} on soybeans. The soybean trifoliate P concentration was greater than the sufficient 2.5 g kg^{-1}in all treatments, but still increased when P was direct applied on soybean with residual BDCST+ST. Later, soybean grain yield shows a response to direct P application on soybean with the residual BND+ST treatment.

Table 2.6 Effect of direct and residual P application on soybean plant and grain P concentration and yield at Scandia in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

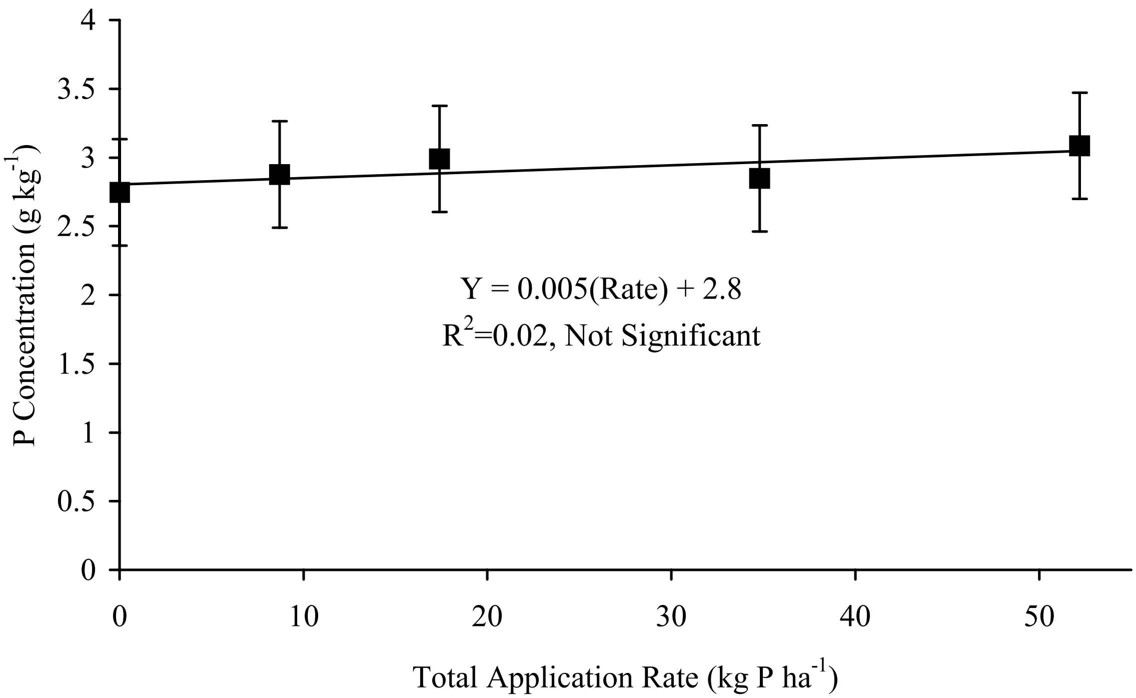
Treatment	Whole Plant (V4)	------Leaf†------	-------------------Grain-------------------	
(kg P ha^{-1})	P Conc. ‡	P Conc.	P Conc.	Yield
	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	2.8 b	2.7 c	4.5	3020 c
HI BDCST+ST	3.2 a	2.8 bc	4.9	3330 b
HI BDCST+ST+SOY	3.2 a	3.1 a	4.9	3400 b
HI BND+ST	3.2 a	3.0 b	4.9	3300 b
HI BND+ST+SOY	3.1 a	3.0 b	4.9	3630 a
Pr > F	<0.03	<0.01	0.17	<0.01

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = uppermost trifoliates without the petioles during pod formation
‡ = samples not collected in 2007

These comparisons clearly show a response of soybean to P, whether residual P applied the year before on corn, or to additional P applied directly to soybean. Two treatments stood out, the HI BDCST+ST+SOY at mid season and the HI BND+ST+SOY at final grain yield. The difference in the responses seen during the growing season was likely a product of P uptake from near the soil surface prior to sampling the trifoliates and P uptake from deeper in the soil as the growing season progressed.

A series of regression models were evaluated to quantify the response of trifoliate P concentration to applied P, but all models were insignificant. The differences in trifoliate P concentration were not due to application rate as Figure 2.6 shows all rates of P application had trifoliate P concentrations above the sufficient level and resulted in no significant model fit. Note that the confidence limits overlap for all the applied rates of P.

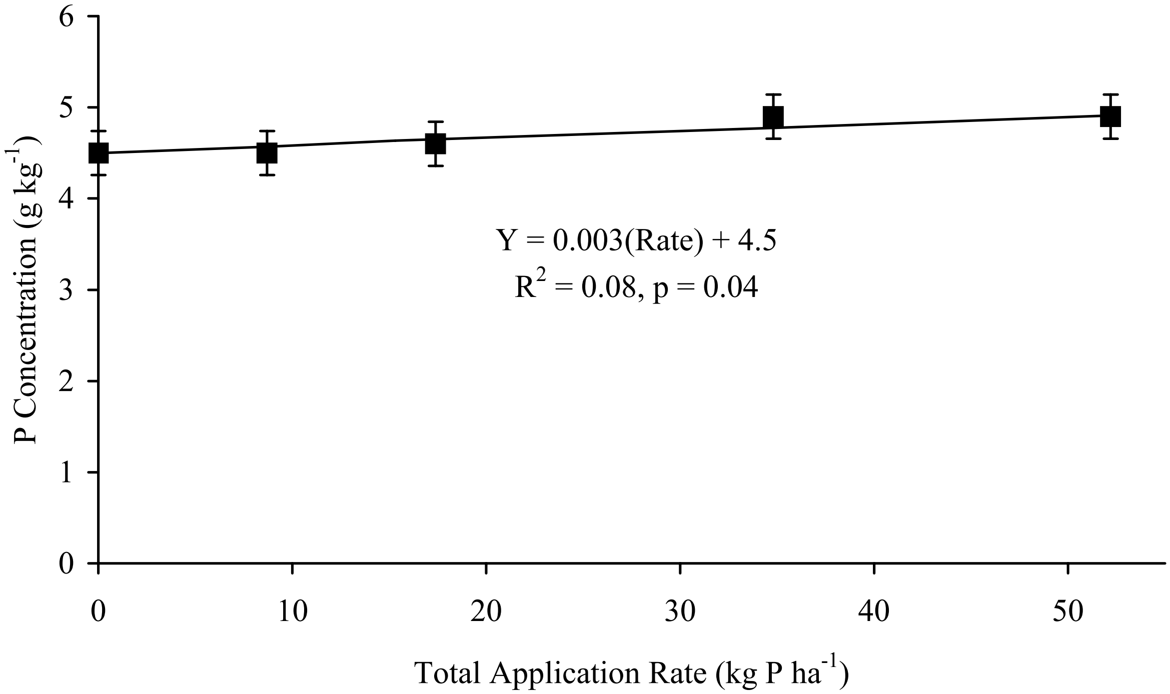
Figure 2.6 Phosphorus fertilizer application and soybean trifoliate P concentration response at Scandia in 2007 and 2008.



Linear model fit using *proc reg*(SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

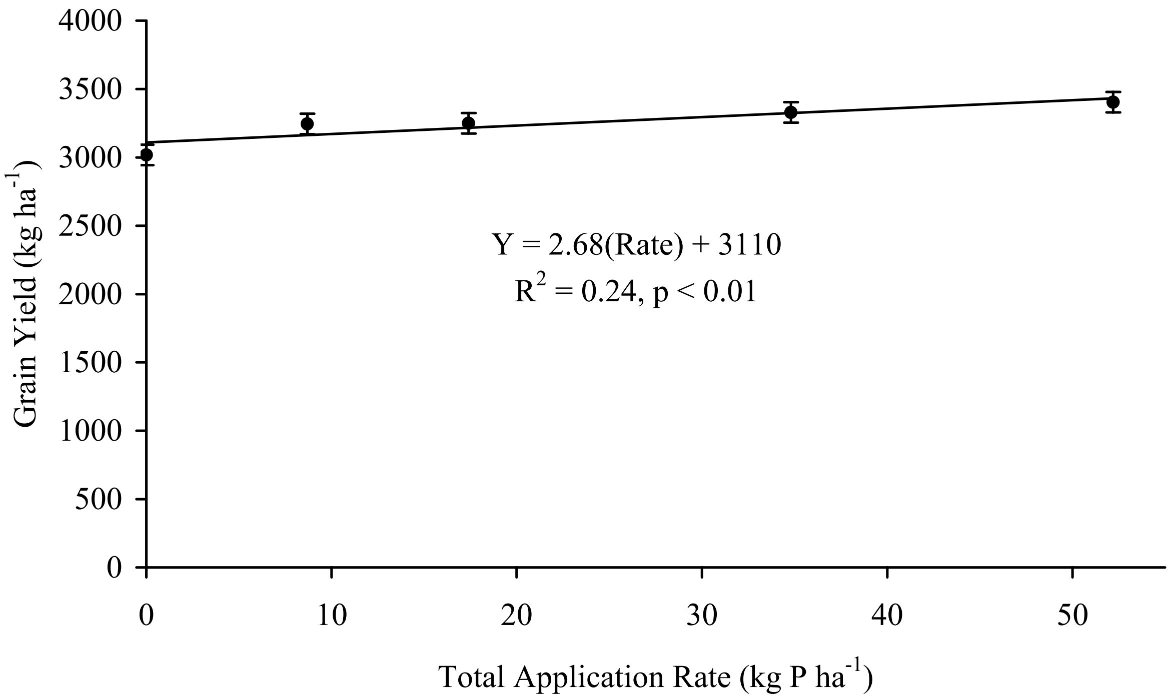
Similar to trifoliate P concentration, both soybean grain P concentration and grain yield were increased by P application (Table 2.5). Significant linear models were found to represent these data and show a slight increase in P concentration and yield with increasing P rate. The response models in Figure 2.7 and 2.8 with small slopes indicate no practical response of grain P concentration or grain yield to P application rate. However, the response on grain yields was significant ($p<0.01$) (Figure 2.8).

Figure 2.7 Phosphorus fertilizer application and soybean grain P concentration response at Scandia in 2007 and 2008.



Linear model fit using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

Figure 2.8 Phosphorus fertilizer application and soybean grain yield response at Scandia in 2007 and 2008.



Linear model fit using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

However, when the residual P responses were evaluated with a starter by placement by rate factorial (Table 2.7), the application of residual starter P increased soybean trifoliate P concentration, but did not affect the grain P concentration or grain yield. Phosphorus placement was not significant in any of the parameters measured in soybean, but application rate was significant for grain P concentration (Table 2.7). With a closer view of Figure 2.7, the comparison of the data point at 17.4 kg P ha^{-1} and 34.8 kg P ha^{-1} may help explain why the rate difference was found in the factorial analysis for grain P concentration and not in the regression model. The 34.8 kg P ha^{-1} rate yielded higher than the 17.4 kg P ha^{-1} rate, which caused a significant difference in the factorial analysis. Unfortunately, the factorial analysis did not reflect the lack of response to P rate evident at this site. None of the direct effects in the factorial analysis in Table 2.7 explained the response shown in soybean grain yield in Table 2.5.

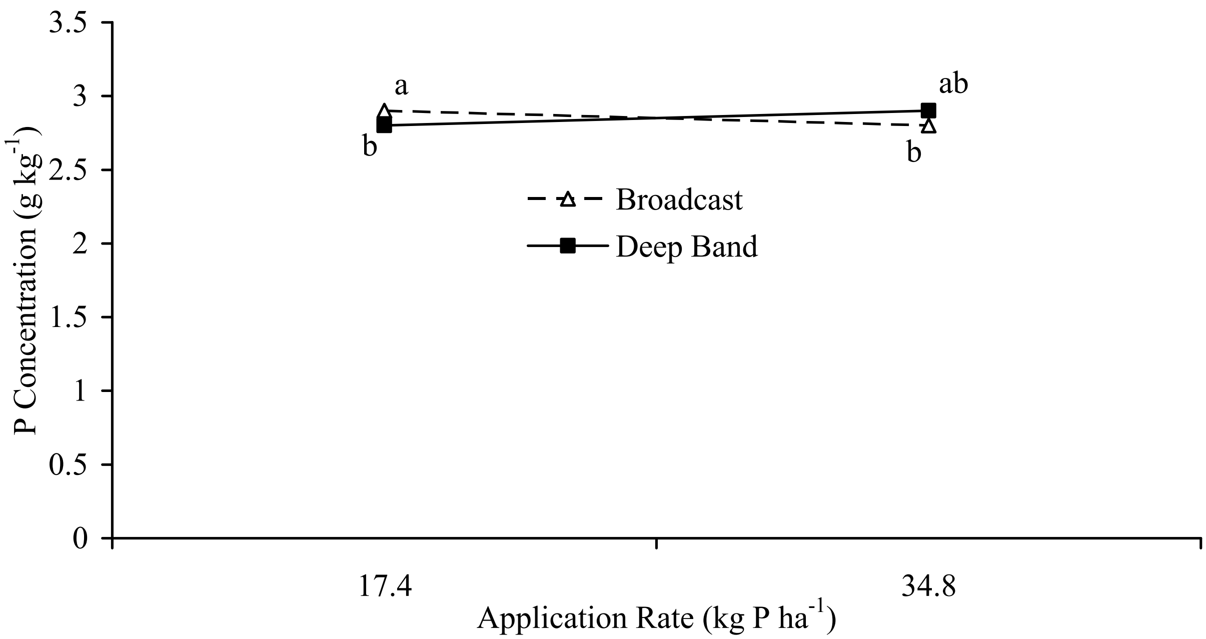
Table 2.7 Factorial analysis of starter fertilizer, placement, and P rate on soybean at Scandia in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

	Whole Plant (V4)	-------Leaf†-------	--------------------Grain--------------------	
Effect	P Conc. (g kg^{-1}) ‡	P Conc. (g kg^{-1})	P Conc. (g kg^{-1})	Yield (kg ha^{-1})
Starter (kg P ha^{-1})				
0	3.0	2.8	4.6	3330
8.7	3.2	2.9	4.8	3280
Placement				
Band	3.1	2.8	4.7	3300
Broadcast	3.1	2.9	4.7	3330
Total (kg P ha^{-1})				
17.4	3.0	2.8	4.6	3280
34.8	3.1	2.8	4.8	3330
F significance				
Starter	<0.01	0.06	0.21	0.22
Placement	0.67	0.28	0.99	0.86
Rate	0.17	0.99	<0.01	0.17
Starter × Placement	0.27	0.59	0.58	0.78
Starter × Rate	0.45	0.35	0.98	0.70
Placement × Rate	0.88	0.08	0.85	0.94
Starter × Placement × Rate	058	0.02	0.59	0.78

† = uppermost trifoliates without the petioles during pod formation
‡ = samples not collected in 2007

The interaction of effects in the factorial analysis was important to understand how these factors behave. Of all parameters, one significant interaction was placement by rate. This interaction illustrated in Figure 2.9, which shows that trifoliate P concentration is affected by placement and rate. However, the data shows that although there were differences in the interaction, these differences were extremely small and of little interest agronomically. Furthermore, it should be noted that all treatments including the check had trifoliate P concentrations greater than the 2.5 g kg^{-1} sufficient level.

Figure 2.9 Interaction of placement and fertilizer application rate on soybean trifoliate P concentration at pod formation at Scandia in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).



Letters indicate significant differences at alpha=0.10

The only factor that appeared to increase yield at Scandia was the direct application of P on soybean following the residual application of P as a starter deep band combination on corn. This management strategy produced 330 kg ha^{-1} more grain than residual starter deep band without the direct application on soybean and 230 kg ha^{-1} greater than the residual starter broadcast with direct application on soybean.

The corn-soybean management that resulted in the best yields at Scandia was to apply a starter deep band combination on corn and direct apply broadcast P on soybean. Although the corn yield was not responsive to application rates above 13.8 kg P ha^{-1}, the soil test P level is still deficient and building the soil test P will result in increased yields over time (Leikam et al., 2003). The projected P removal rates by the crops in this rotation at Scandia are greater than the P application rates and would theoretically decrease the soil P concentration (discussed in the following chapter). Although recommendations for P application greater than the responsive rate in this study may be difficult to consider, it should be realized that the P data used by Leikam et al. (2003) was much more complete and provides a more thorough recommendation for crop response and thus increased P application may be warranted in this region.

Ottawa

Corn

Corn at Ottawa was less responsive than at Scandia. The data in Table 2.8 includes treatments 1-10 and all three years of this study. Table 2.8 shows that a response to P was observed in plant P uptake at V6, earleaf P concentration, grain P concentration, and grain yield.

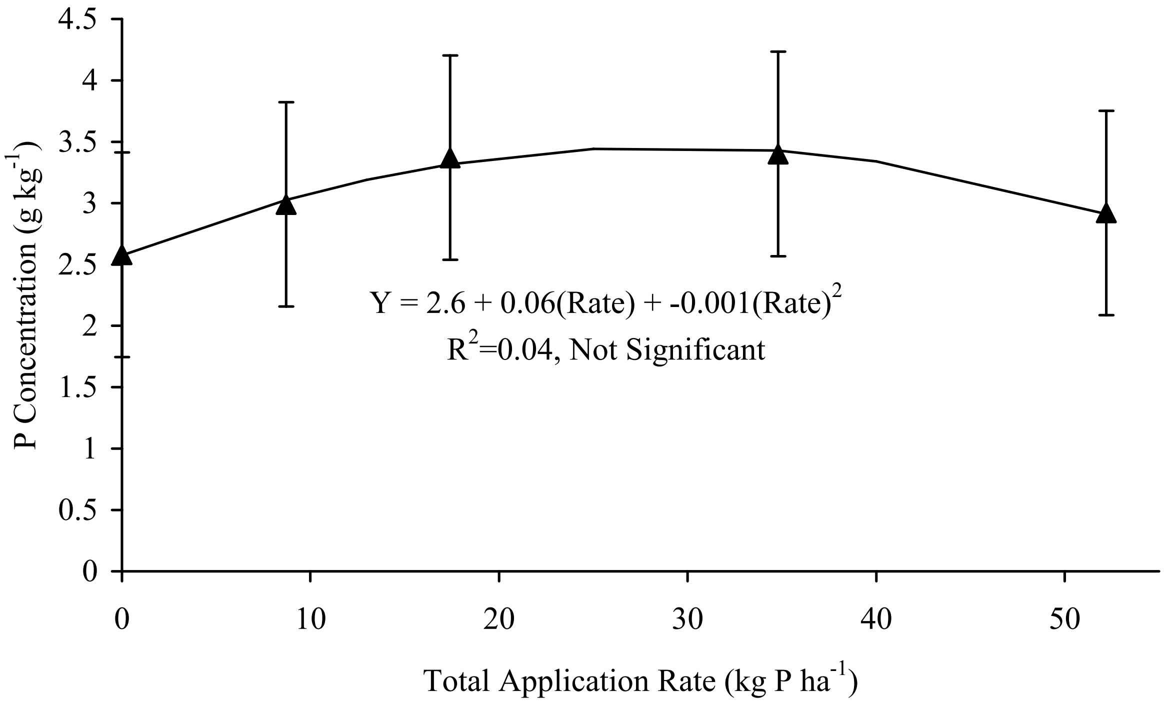
Table 2.8 Effect of phosphorus treatments on corn plant and grain P concentration and yield at Ottawa in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	------------Whole Plant (V6)------------			---Leaf†---	-----------Grain-----------	
(kg P ha^{-1})	P Conc. ‡	Biomass‡	P Uptake‡	P Conc.	P Conc.	Yield
	(g kg^{-1})	(kg ha^{-1})	(kg P ha^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	3.6 f	730	2.6 e	2.2 f	2.3 e	5240 d
ST	4.0 cd	770	3.0 bcde	2.4 ef	2.4 de	5650 bc
LOW BDCST	3.8 def	770	2.9 cde	2.4 def	2.6 bc	5750 abc
LOW BDCST+ST	4.0 cd	880	3.4 abc	2.5 cde	2.5 bcd	5960 abc
LOW BND	3.9 cde	800	3.0 bcd	2.5 bcde	2.5 cd	6040 a
LOW BND+ST	4.0 bcd	790	3.0 bcde	2.6 abcd	2.6 bcd	5980 ab
HI BDCST	3.7 ef	770	2.8 de	2.5 bcde	2.8 a	5900 abc
HI BDCST+ST	4.3 ab	810	3.4 ab	2.7 abc	2.7 ab	5970 abc
HI BND	4.1 abc	740	2.9 cde	2.7 ab	2.6 abc	5850 abc
HI BND+ST	4.3 a	830	3.5 a	2.8 a	2.6 abc	5640 c
Pr > F	<0.01	0.40	0.02	<0.01	<0.01	<0.01

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = ear leaf
‡ = samples not collected in 2006

Rate response models were fit to the significant factors in Table 2.8. Although a response to P was observed in corn plant P uptake at V6 and the quadratic model appears to represent the data, it was not a significant model. The error bars represent the standard error of the mean, which shows a high degree of variability in this rate response (Figure 2.10).

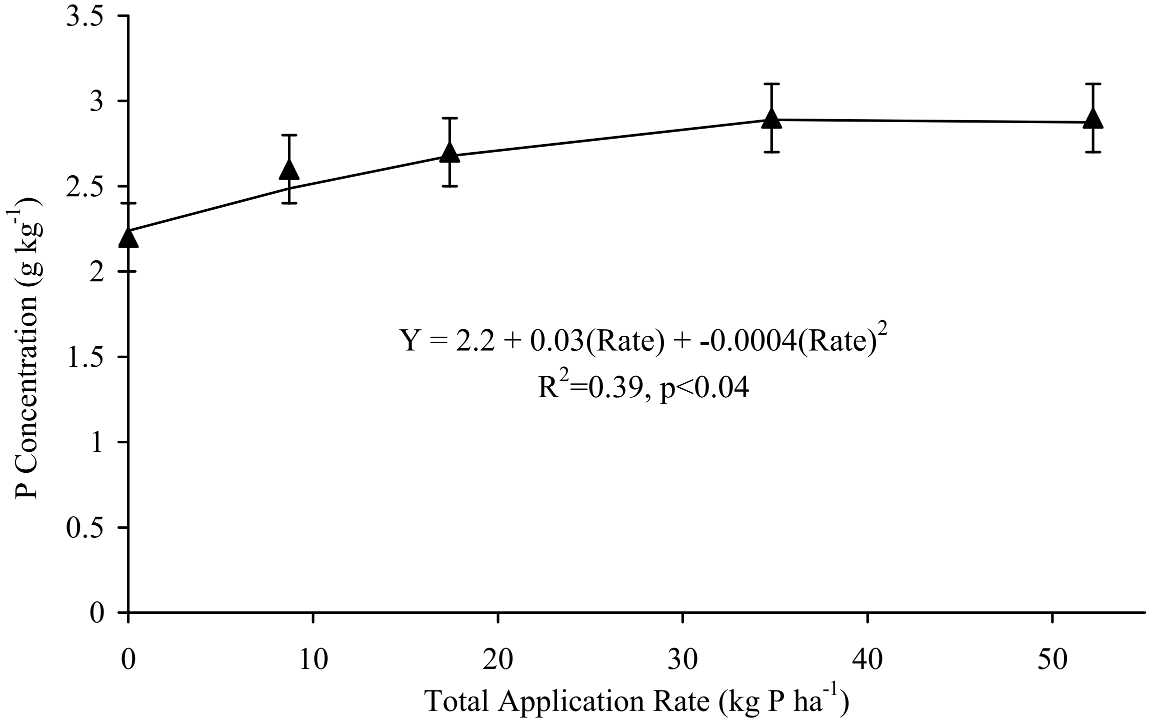
Figure 2.10 Response of P fertilizer application on corn P uptake at the V6 stage response at Ottawa in 2007 and 2008.



Quadratic model fit using *proc reg*(SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

The ear leaf P concentration response shown in Table 2.8 was described with a quadratic response model (Figure 2.11). The lowest application rate does not fit the model as other rates do, but it is clear that earleaf P concentration is increasing at the low application rates. This model shows corn ear leaf P concentration increased up to 34.8 kg P ha^{-1} application rate. All P application rates increased the earleaf P concentration above the critical value and thus excess P was taken up by the plants during this stage of growth when fertilization took place.

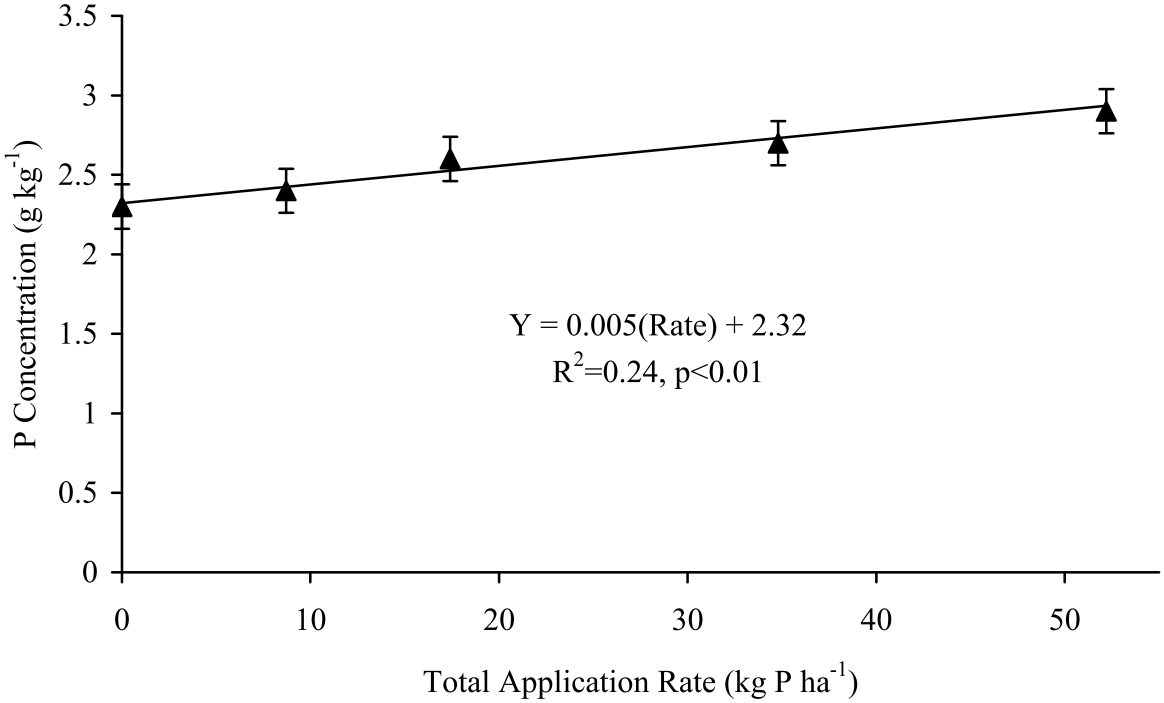
Figure 2.11 Response of P fertilizer application on corn ear leaf P concentration response at Ottawa in 2007 and 2008.



Linear model fit using *proc reg*(SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

A linear response was found to significantly describe corn grain P response to P application (Figure 2.12). Although the model fit is not ideal, it illustrates that P was getting into the plant late in the season and all application rates increased the P concentration in the grain.

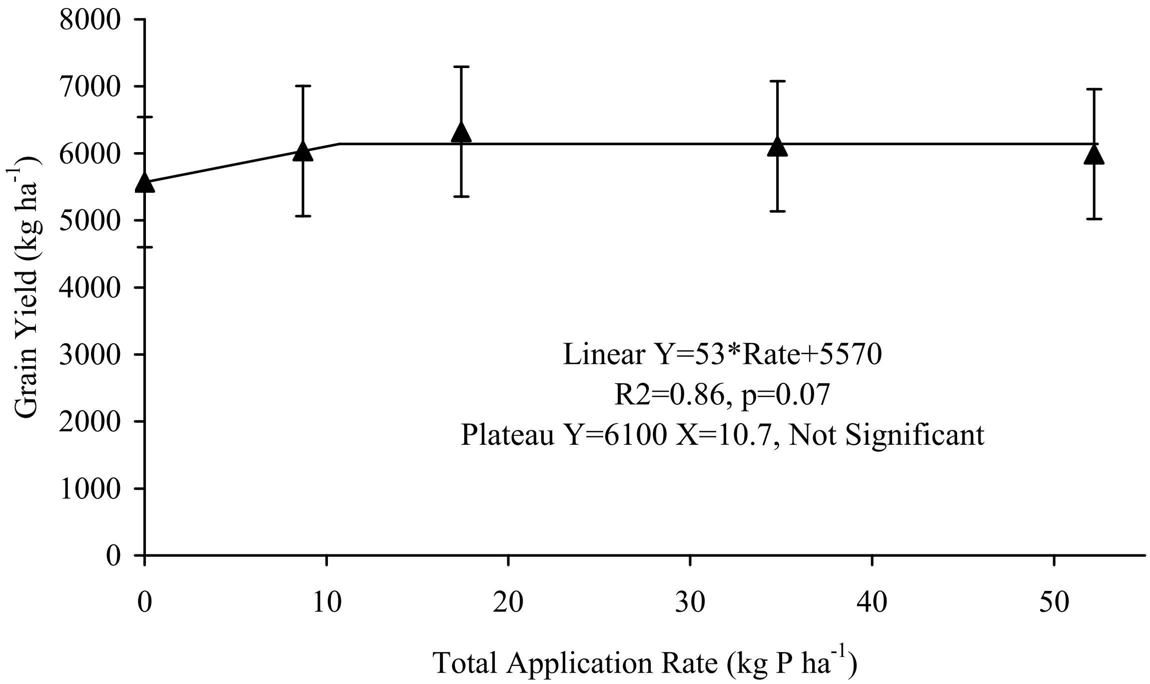
Figure 2.12 Response of P fertilizer application on corn grain P concentration response at Ottawa in 2007 and 2008.



Linear model fit using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

Different models were used to try to quantify the response of corn grain yield at Ottawa to applied P. The data is displayed in Figure 2.13 and shows that the data included in this model has a very high standard error. A linear plateau model was used as it best fit the data, but only produced a significant relationship in the linear portion, not the plateau. So, although an inflection point cannot be established, there was a response to some level of application, even if it was only the low rate.

Figure 2.13 Response of P fertilizer application on corn grain yield response at Ottawa in 2007 and 2008.



Linear plateau model fit using *proc nlmixed* (SAS, 2007)
Error bars represent the standard error of the means.
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; 52.2 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast, 17.4 kg P ha^{-1} broadcast on soybean

A factorial analysis was included to further investigate the P responses in Table 2.9 to see if starter, placement, rate or an interaction of these factors can show additional information as to the reasons for the responses. The data in Table 2.9 shows significant main effects in all measurements except grain yield. There was an interaction for starter by rate for P concentration in the plant tissue at V6, but this interaction was not present in the plant P uptake at V6.

Table 2.9 Factorial analysis of starter fertilizer, placement, and P rate in corn at Ottawa in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

	------Whole Plant (V6)------		---Leaf†---	-------------Grain-------------	
Effect	P Conc. ‡ ($g\ kg^{-1}$)	P Uptake‡ ($kg\ P\ ha^{-1}$)	P Conc. ($g\ kg^{-1}$)	P Conc. ($g\ kg^{-1}$)	Yield ($kg\ ha^{-1}$)
Starter ($kg\ P\ ha^{-1}$)					
0	3.9	2.9	2.6	2.6	5890
8.7	4.1	3.3	2.6	2.6	5890
Placement					
Band	4.1	3.1	2.7	2.6	5880
Broadcast	3.9	3.1	2.5	2.7	5900
Rate ($kg\ P\ ha^{-1}$)					
17.4	3.9	3.1	2.5	2.5	5930
34.8	4.1	3.1	2.7	2.7	5840
F significance					
Starter	<0.01	<0.01	0.18	0.91	0.99
Placement	0.03	0.89	0.01	0.15	0.85
Rate	0.02	0.60	0.01	<0.01	0.38
Starter × Placement	0.14	0.27	0.91	0.27	0.20
Starter × Rate	0.04	0.16	0.75	0.60	0.50
Placement × Rate	0.23	0.32	0.75	0.54	0.12
Starter × Placement × Rate	0.24	0.50	0.71	0.74	0.98

† = ear leaf
‡ = samples not collected in 2006

Significant starter main effects only occurred in the early corn P uptake data. This was similar to data at Scandia that showed early plant responses to starter because of seedlings taking up P at shallow soil depths. Placement and rate and the interactions were not significant for early plant P uptake. All later samples were not significant for effects due to starter. However, in the middle of the growing season when ear leaves were sampled, there was a significant effect of placement and rate. The mean data in Table 2.9 shows that deep band applied P increased the ear leaf P concentration. Interestingly, applying a high rate of P increased the P concentration in the ear leaf tissue the same amount as deep band application. Grain P concentration had a rate effect similar to that of the ear leaves.

Greater and clearer P responses were seen early in the growing season at Ottawa that were not evident in grain yield. Although Ottawa soil test P is in the responsive range, responses were likely limited by late season drought stress. Increased P concentration in the grain when high rates of P were used indicated that additional P was accumulated or taken up by the plant, but grain production was limited, so the crop was not able to utilize that P to produce more grain.

Soybean

Ottawa soybean P response was treated similar to Scandia by evaluating all treatments from 2007 and 2008. This data, in Table 2.10, shows only biomass P concentration at V4 and grain P concentration responded to P application. Although V4 P concentration responded to P, P uptake at V4 did not. The treatment means in Table 2.10 generally show that grain P concentration increased when high rates of residual P was applied to the previous corn crop or when soybeans were fertilized directly.

Table 2.10 Effect of phosphorus treatments on soybean plant and grain P concentration and yield at Ottawa in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	------------Whole Plant (V4)------------			---Leaf†---	----------Grain----------	
(kg P ha^{-1})	P Conc. ‡	Biomass‡	P Uptake‡	P Conc.	P Conc.	Yield
	(g kg^{-1})	(kg ha^{-1})	(kg P ha^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	2.9 e	530	1.5	2.8	4.9 e	1630
ST	3.2 abc	550	1.7	2.8	5.0 de	1800
LOW BDCST	2.8 e	580	1.6	2.6	4.8 e	1800
LOW BDCST+ST	3.0 bcde	540	1.6	2.8	5.1 cde	1770
LOW BND	3.0 bcde	520	1.6	2.7	5.1 de	1760
LOW BND+ST	3.0 cde	610	1.8	2.8	5.2 bcd	1800
HI BDCST	3.0 cde	580	1.7	2.7	5.0 de	1720
HI BDCST+ST	3.0 bcde	580	1.7	2.9	5.5 a	1860
HI BND	2.9 de	620	1.8	2.8	5.3 abcd	1870
HI BND+ST	3.1 abcd	560	1.7	2.8	5.4 ab	1780
HI BDCST+ST+SOY	3.2 ab	570	1.8	2.9	5.5 a	1740
HI BDCST+ST+SOY	3.3 a	590	1.9	3.1	5.4 abc	1810
Pr > F	0.04	0.79	0.12	0.13	<0.01	0.22

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = uppermost trifoliates without the petioles during pod formation
‡ = samples not collected in 2007

The direct and residual fertilization effects on soybean at Ottawa are given in Table 2.11. The mean comparison Table 2.11 shows that residual or direct fertilization increased the grain P concentration above the check, but there was no difference where P was applied on soybean and where the soybean crop relied on residual P from the corn crop.

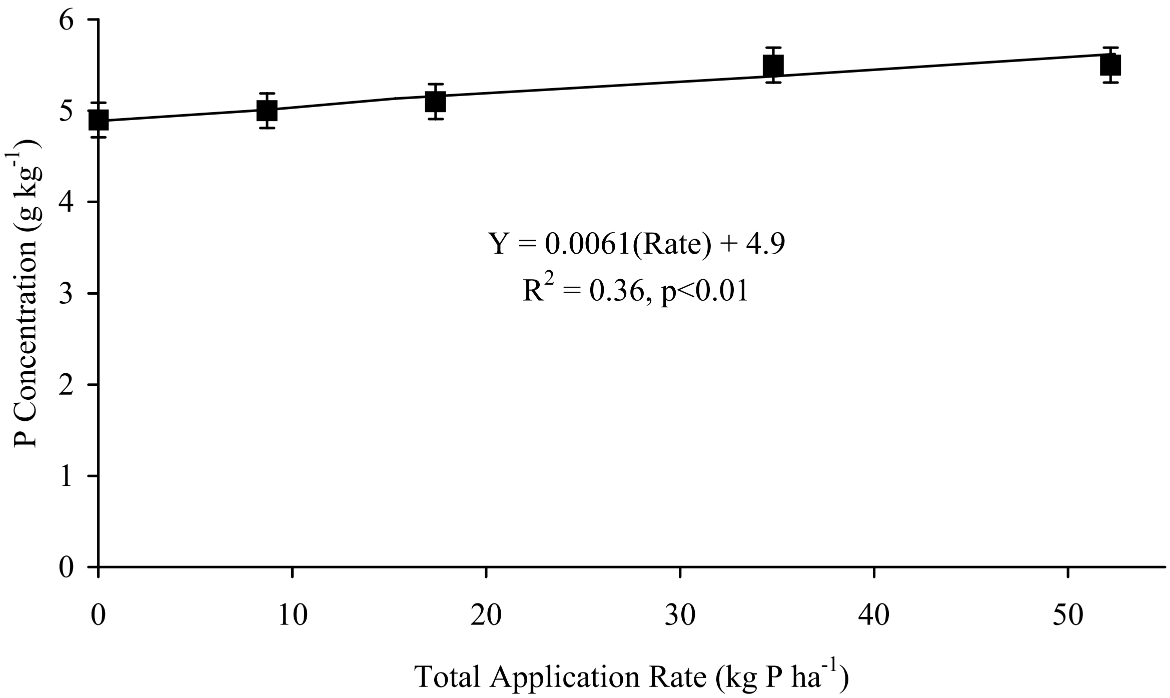
Table 2.11 Effect of direct and residual P application on soybean plant and grain P concentration and yield at Ottawa in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment (kg P ha^{-1})	Whole Plant (V4) ‡ P Conc. (g kg^{-1})	Grain P Conc. (g kg^{-1})
CHECK	2.9	4.9 b
HI BDCST+ST	3.0	5.5 a
HI BDCST+ST+SOY	3.2	5.5 a
HI BND+ST	3.1	5.4 a
HI BND+ST+SOY	3.3	5.4 a
Pr > F	0.12	<0.01

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
‡ = samples not collected in 2007

A linear model was used to show the increase in grain P concentration with application rate (Figure 2.13). Although there was a significant linear increase, the rate of increase was small (slope = 0.006). The factorial analysis showed that grain P concentration responded to higher rates of P and showed that starter P application was important and increased grain P concentration 0.3 g kg^{-1}. Other factors and interactions were not significantly different (Table 2.12).

Figure 2.14 Effect of P fertilizer application on soybean grain P concentration response at Ottawa in 2007 and 2008.



Linear model fit using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter, 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast

Table 2.12 Factorial analysis of starter fertilizer, placement, and P rate on soybean at Ottawa in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

Effect	Whole Plant (V4) ‡ P Conc. (g kg^{-1})	Grain P Conc. (g kg^{-1})
Starter (kg P ha^{-1})		
0	3.0	5.0
8.7	3.0	5.3
Placement		
Band	3.0	5.2
Broadcast	3.0	5.1
Total (kg P ha^{-1})		
17.4	3.0	5.0
34.8	3.0	5.3
F significance		
Starter	0.19	<0.01
Placement	0.52	0.16
Rate	0.41	<0.01
Starter × Placement	0.61	0.17
Starter × Rate	0.61	0.51
Placement × Rate	0.54	0.67
Starter × Placement × Rate	0.14	0.71

‡ = samples not collected in 2007

The data from Ottawa taken early in the growing season suggested a response to P may occur, but did not carry through to grain yield in either corn or soybean. This may have been impacted by challenging weather events including flood conditions early in the growing season in 2007, and abnormally dry and hot conditions late in the season causing restricted yield responses in both crops. Additional conclusions regarding precipitation will be discussed at the end of this chapter.

Manhattan

Soybean

The Manhattan soybean data was evaluated the same way as Scandia and Ottawa. The effects on soybean were viewed as the residual from the previous crop and direct application on soybean. The results from this analysis are in Table 2.13 and show no significant differences due to residual or direct fertilization on soybean growth. Thus it was concluded that soybean did not respond to P fertilization at Manhattan. The most likely reason for the lack of response is the soil test P level was high (Table 2.1) and crop response to P would not be expected.

Table 2.13 Effect of phosphorus treatments on soybean plant and grain P concentration and yield at Manhattan in 2007 and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	------------Whole Plant (V4)------------			---Leaf†---	-----------Grain-----------	
(kg P ha^{-1})	P Conc.	Biomass	P Uptake	P Conc.	P Conc.	Yield
	(g kg^{-1})	(kg ha^{-1})	(kg P ha^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	3.3	1270	4.2	3.2	6.1	2280
ST	3.3	1140	3.7	3.1	6.4	2350
LOW BDCST	3.3	1260	4.2	3.2	6.4	2340
LOW BDCST+ST	3.2	1300	4.2	3.2	6.5	2300
LOW BND	3.2	1230	3.9	3.2	6.3	2370
LOW BND+ST	3.1	1110	3.4	3.1	6.3	2200
HI BDCST	3.3	1270	4.2	3.2	6.5	2260
HI BDCST+ST	3.4	1170	4.0	3.1	6.4	2280
HI BND	3.3	1310	4.3	3.2	6.2	2200
HI BND+ST	3.3	1170	3.9	3.2	6.3	2350
HI BDCST+ST+SOY	3.4	1260	4.3	3.3	6.7	2320
HI BDCST+ST+SOY	3.3	1400	4.6	3.2	6.6	2280
Pr > F	0.11	0.38	0.19	0.90	0.11	0.18

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = uppermost trifoliates without the petioles during pod formation

Soybean data at Manhattan was also evaluated by year. Since there was a three year rotation at Manhattan, 2006 was considered a setup year for soybean (there was not a residual application to evaluate), so 2006 data was not analyzed. In 2007, there was potential residual effect from application on the previous sorghum crop, so data was treated similar to a two year rotation. In 2008, soybean data reflects the residual application of P on wheat in 2006, and sorghum in 2007, and direct application on soybean in 2008. Using this different approach, there was not a significant response to P in any of the measurements taken in 2007 or 2008 and thus conclusions that soybean did not respond to P were confirmed.

Wheat

Wheat data at Manhattan was analyzed to evaluate the effect of direct application of P on the wheat crop. Therefore, 2006, 2007, and 2008 data for treatments 1-10 were used to determine if there was a significant response to P application. Table 2.14 shows this data and that all plant measurements did not respond to P application.

Table 2.14 Effect of phosphorus treatments on wheat plant and grain P concentration and yield at Manhattan in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	---------Whole Plant (feekes 6)---------			---Leaf†---	-----------Grain-----------	
(kg P ha^{-1})	P Conc. ‡ (g kg^{-1})	Biomass‡ (kg ha^{-1})	P Uptake‡ (kg P ha^{-1})	P Conc. (g kg^{-1})	P Conc. (g kg^{-1})	Yield (kg ha^{-1})
CHECK	2.4	510	1.3	2.5	3.3	2760
ST	3.5	1040	3.6	2.6	3.5	2920
LOW BDCST	3.0	680	2.1	2.6	3.4	2950
LOW BDCST+ST	3.0	1000	3.0	2.7	3.4	2950
LOW BND	2.5	560	1.4	2.6	3.2	2770
LOW BND+ST	3.0	1000	3.0	2.6	3.3	2930
HI BDCST	2.8	710	2.0	2.6	3.4	3000
HI BDCST+ST	3.5	1050	3.6	2.7	3.5	2980
HI BND	2.8	660	1.9	2.6	3.5	2900
HI BND+ST	2.9	1040	3.2	2.6	3.3	2860
Pr > F	0.20	0.52	0.29	0.57	0.77	0.38

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = flag leaf
‡ = samples not collected in 2006 or 2007

Sorghum

The sorghum crop was treated similar to wheat at Manhattan by evaluating the direct application of P on grain sorghum using treatments 1-10. The data presented in Table 2.15

shows that there was no response to P in grain sorghum, similar to wheat and soybean at Manhattan.

Table 2.15 Effect of phosphorus treatments on sorghum plant and grain P concentration and yield at Manhattan in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	-----------Whole Plant (GS2)-----------			---Leaf†---	-----------Grain-----------	
($kg\ P\ ha^{-1}$)	P Conc.	Biomass	P Uptake	P Conc.	P Conc.	Yield
	($g\ kg^{-1}$)	($kg\ ha^{-1}$)	($kg\ P\ ha^{-1}$)	($g\ kg^{-1}$)	($g\ kg^{-1}$)	($kg\ ha^{-1}$)
CHECK	3.3	1860	3.2	3.0	2.8	4970
ST	3.1	1880	3.1	3.1	2.9	5180
LOW BDCST	3.4	1880	3.2	3.1	2.9	4980
LOW BDCST+ST	3.3	1870	3.2	3.1	2.9	5140
LOW BND	3.2	1990	3.2	3.1	2.9	5140
LOW BND+ST	3.5	2010	3.1	3.0	2.9	5070
HI BDCST	3.4	2010	3.2	3.1	3.0	5250
HI BDCST+ST	3.3	1830	3.1	3.0	3.1	4830
HI BND	3.2	1920	3.2	3.1	2.9	5170
HI BND+ST	3.4	1940	3.2	3.1	2.9	5380
Pr > F	0.60	0.62	0.23	0.28	0.21	0.16

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = flag leaf

It was recognized there could be confounding effects from previous year P application on wheat or sorghum at Manhattan. For example, application on sorghum in 2007 could affect the following 2008 wheat P response. Therefore, responses to P were evaluated for each year, which resulted in similar conclusions to the three year data in Table 2.14 and 2.15. Both methods of analysis on wheat and sorghum demonstrated that Manhattan was not a responsive site to P application. With the high soil test P (55.4 and 19.9 mg kg^{-1} for 0-7.6 and 7.6-15 cm respectively), this conclusion was expected.

Tribune

Wheat

Tribune wheat was treated similar to Manhattan wheat. The data in Table 2.16 shows P responses to direct fertilization of wheat in 2006, 2007, and 2008. At Tribune, differences were not found early or mid season, but P responses were significant in grain P concentration and grain yield. The treatment means show sporadic results and indicate the cause of the P response may be hard to identify.

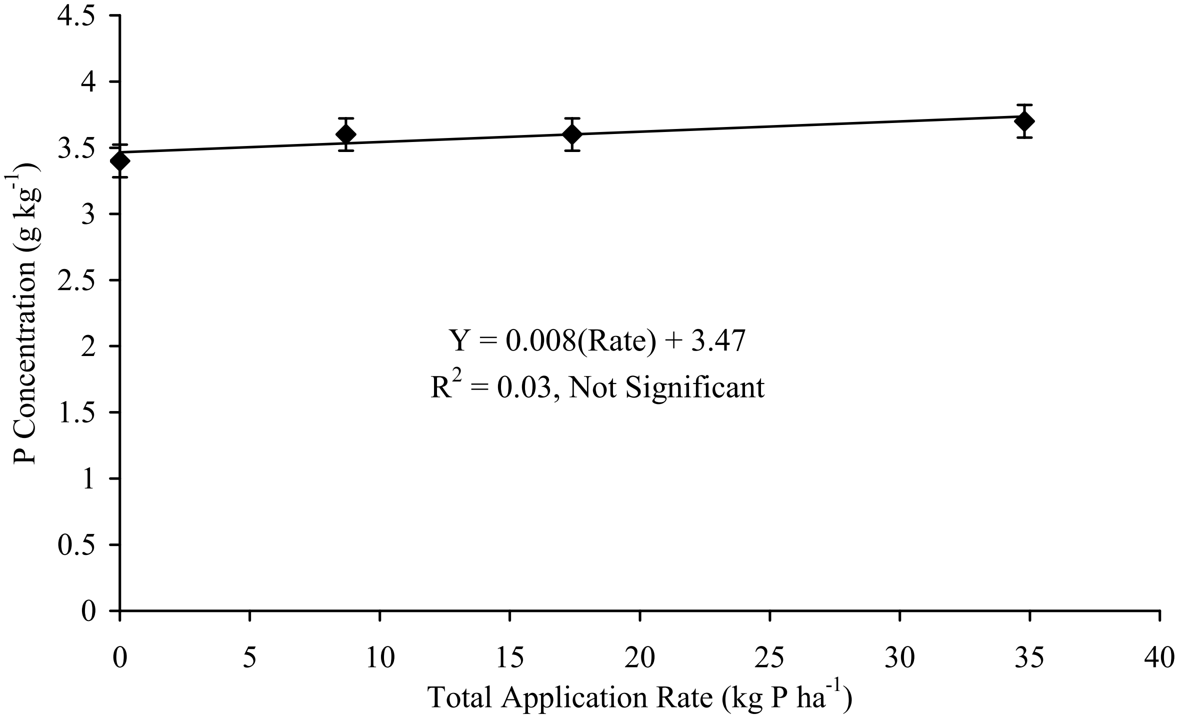
Table 2.16 Effect of phosphorus treatments on wheat plant and grain P concentration and yield at Tribune in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	---------Whole Plant (feekes 6)---------			---Leaf†---	-----------Grain-----------	
(kg P ha^{-1})	P Conc. ‡	Biomass‡	P Uptake‡	P Conc.	P Conc.	Yield
	(g kg^{-1})	(kg ha^{-1})	(kg P ha^{-1})	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	1.9	1400	2.5	2.5	3.4 c	1960 abc
ST	2.5	1430	2.9	2.6	3.6 ab	1880 bc
LOW BDCST	2.2	1590	3.3	2.6	3.5 bc	2050 a
LOW BDCST+ST	2.7	870	2.1	2.7	3.6 ab	1800 c
LOW BND	2.0	1770	3.5	2.5	3.5 abc	2000 ab
LOW BND+ST	2.1	1950	3.7	2.5	3.5 bc	2020 ab
HI BDCST	2.1	2580	5.3	2.6	3.6 ab	2020 ab
HI BDCST+ST	2.6	1580	3.3	2.5	3.7 a	1890 bc
HI BND	2.2	2300	5.6	2.7	3.4 c	1950 abc
HI BND+ST	2.1	2490	5.1	2.6	3.6 ab	2110 a
Pr > F	0.20	0.38	0.41	0.18	0.05	0.07

Letters indicate significant differences at alpla ≤ 0.10, data without letters are not significantly different
† = flag leaf
‡ = samples not collected in 2006 or 2007

Regression models were applied to grain P concentration and grain yield to determine if a significant rate response was contributing to the treatment differences. Figure 2.15 and 2.16 show these models.

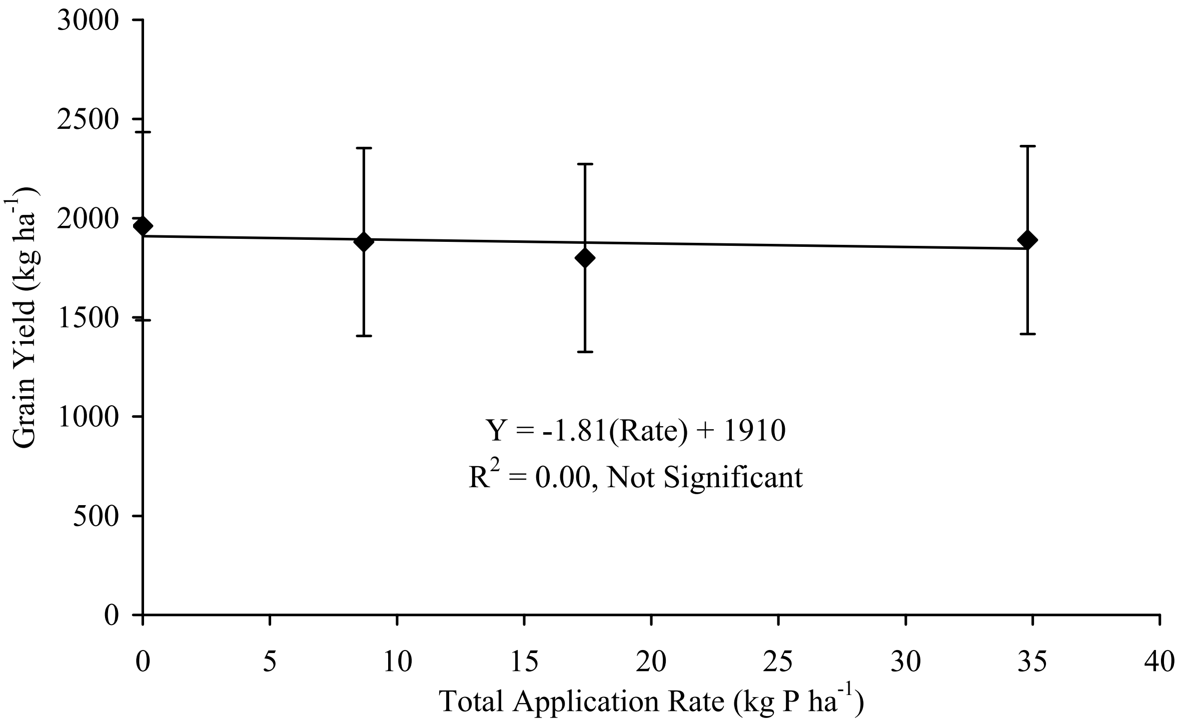
Figure 2.15 Effect of P fertilizer application on wheat grain P concentration response at Tribune in 2006, 2007, and 2008.



Linear fit calculated using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means.
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter , 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast

A linear model was used to represent the rate response for grain P concentration because there was not a significant model fit. The insignificant linear model indicates a rate response to P could not be identified as the factor controlling grain P concentration (Figure 2.15). Similarly, the linear model used in the grain yield response model was not significant and thus yield differences were not due to P rate (Figure 2.16).

Figure 2.16 Effect of P fertilizer application on wheat grain yield response at Tribune in 2006, 2007, and 2008.



Linear fit calculated using *proc reg* (SAS, 2007)
Error bars represent the standard error of the means.
Treatments used for total application rate include: 0 rate = 0 kg P ha^{-1}; 8.7 rate = 8.7 kg P ha^{-1} starter; 17.4 rate = 8.7 kg P ha^{-1} starter , 8.7 kg P ha^{-1} broadcast; 34.8 rate = 8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast

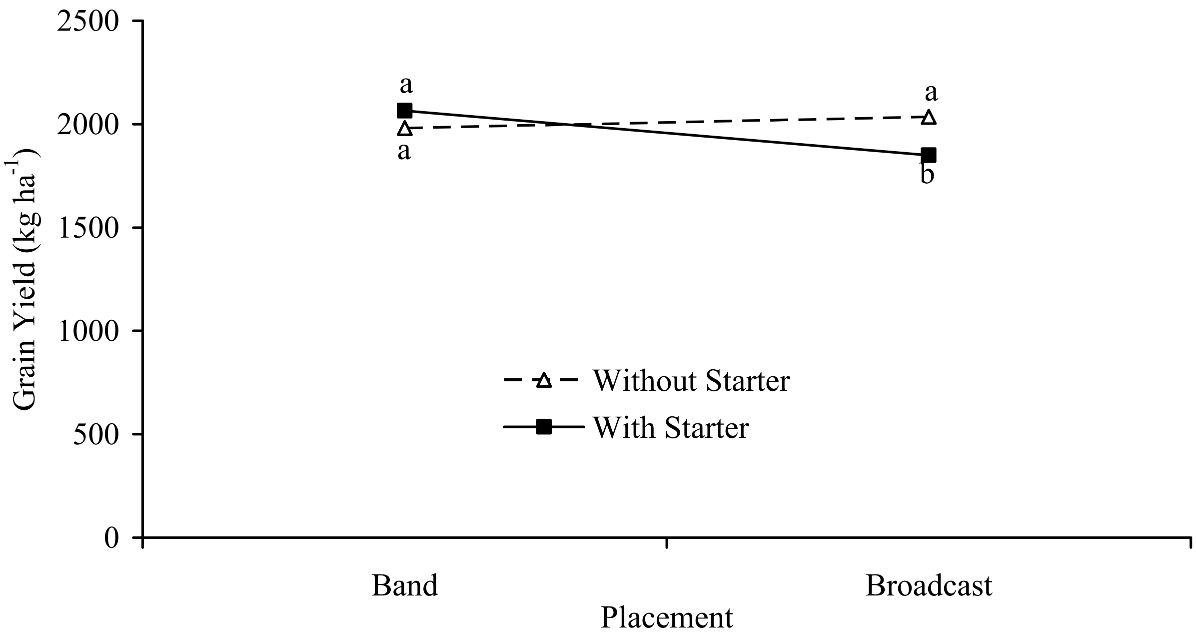
A 2x2x2 factorial was used to investigate the starter, placement, and rate factors contributing to grain P concentration and grain yield differences at Tribune. This analysis identified two significant main effects in grain P concentration, which included the application of starter and broadcast applied P that both increased the grain P concentration (Table 2.17). Interactions were evaluated, but not found significant in grain P concentration. Grain yield was significantly affected by placement, but was opposite that of grain P concentration as band applied P increased grain yields, not broadcast P. This is confusing since a similar trend should occur in both grain P concentration and grain yield. This indicates that early season growth in an extremely water limited environment may not be beneficial.

Table 2.17 Factorial analysis of starter fertilizer, placement, and P rate on wheat at Tribune in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Effect	--------------------------------Grain--------------------------------	
	P Concentration (g kg^{-1})	Yield (kg ha^{-1})
Starter (kg P ha^{-1})		
0	3.5	2010
8.7	3.6	1960
Placement		
Band	3.5	2020
Broadcast	3.6	1940
Rate (kg P ha^{-1})		
17.4	3.5	1970
34.8	3.6	1990
F significance		
Starter	0.03	0.29
Placement	0.04	0.10
Rate	0.31	0.66
Starter × Placement	0.60	0.01
Starter × Rate	0.27	0.21
Placement × Rate	0.22	0.88
Starter × Placement × Rate	0.07	0.85

The interaction of starter by placement was highly significant in grain yield (Table 2.17). Figure 2.17 was generated to view the starter by placement interaction, which shows that broadcast applied P with starter yields significantly less than all other starter and placement combinations. This outcome does not follow agronomic expectations because the LOW BDCST+ST treatment was thought to be superior to the LOW BDCST treatment. However, in a water limited environment, especially limited during vegetative growth and early stages of reproductive growth, enhancing early growth could utilize more stored water early in the season exacerbating mid-season drought stress.

Figure 2.17 Interaction of starter and placement of P fertilizer in wheat grain yield at Tribune in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).



Letters indicate significant differences at alpha=0.10

In general, wheat P responses at Tribune have not led to definitive conclusions as to what P management strategies impact wheat growth, P concentration, and yield. When an additional analysis (by year) was conducted to see if the additive effects of previous crops were overlooked, data responded similarly in all factors except grain yield, which was shown to not respond to P. Again, both analyses make the conclusion that wheat at Tribune did not consistently respond to P fertilizer, which was expected because the soil test P is high (74.1 and 31.3 mg kg^{-1} for 0-7.6 and 7.6-15 cm respectively) and soil moisture is generally limited.

Sorghum

The response of grain sorghum to P treatments over all three years of this study is summarized in Table 2.18. This data shows that the P treatments were statistically similar and thus there was no response to P at Tribune in sorghum. Similar results were found when years were separated and analyzed independently.

Table 2.18 Effect of phosphorus treatments on sorghum plant and grain P concentration and yield at Tribune in 2006, 2007, and 2008. Calculated using *proc mixed* (SAS 2007).

Treatment	-------Leaf†-------	--------------------Grain--------------------	
(kg P ha^{-1})	P Conc.	P Conc.	Yield
	(g kg^{-1})	(g kg^{-1})	(kg ha^{-1})
CHECK	2.3	2.4	3140
ST	2.4	2.3	3530
LOW BDCST	2.4	2.5	3140
LOW BDCST+ST	2.5	2.5	3240
LOW BND	2.5	2.6	3160
LOW BND+ST	2.5	2.6	3070
HI BDCST	2.5	2.5	3090
HI BDCST+ST	2.8	2.5	3030
HI BND	2.5	2.6	3170
HI BND+ST	2.5	2.6	3170
Pr > F	0.11	0.55	0.96

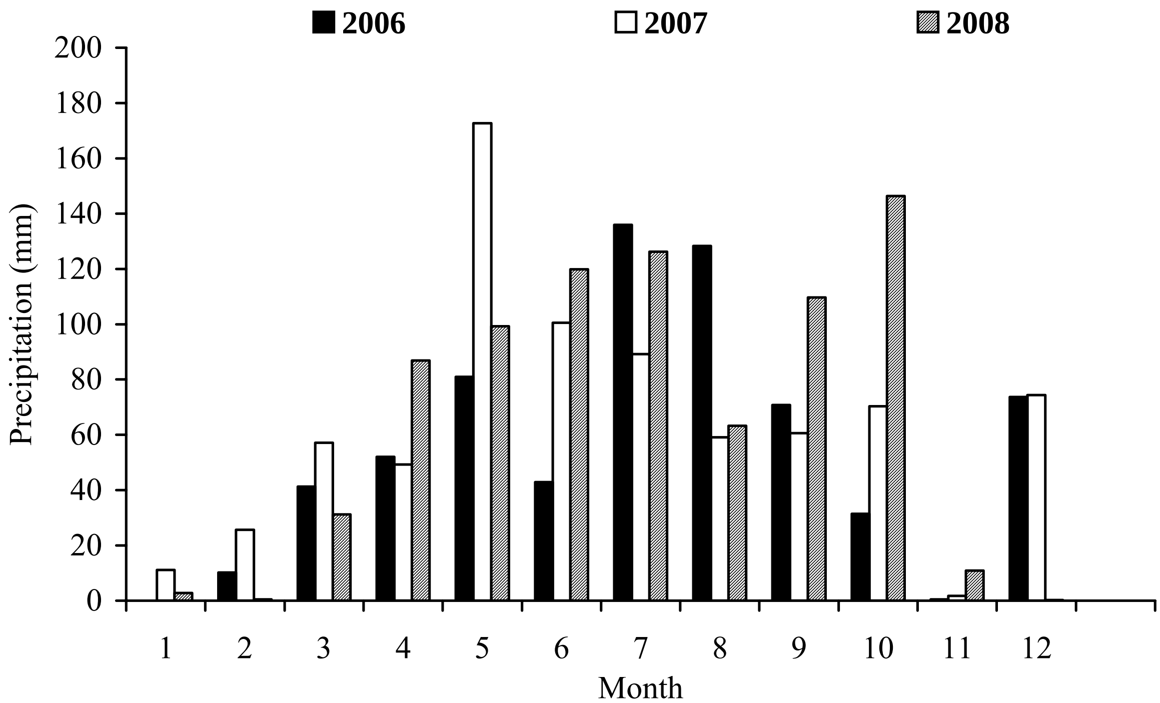
Treatment comparison alpla = 0.10
† = flag leaf

Precipitation Effects and Interactions

Precipitation totals and distribution was likely the controlling factor that either allowed or restricted P response in this study. Figures 2.18, 2.19, 2.20, and 2.21 graphically display the precipitation totals for each month during years in which crops were grown at Scandia, Ottawa, Manhattan, and Tribune, respectively.

Crop response was most consistent at Scandia, which was also one of the low soil test P sites with high yield potential. The long term mean annual precipitation (30 year) for Scandia was 710 mm, but the opportunity for irrigation at this site, with water available for irrigation during June, July and August, allows for more even distribution of water. The bulk of precipitation comes between May and October at Scandia, which matches well with summer crop production.

Figure 2.18 Monthly precipitation total for each month in Scandia (2006-2008).

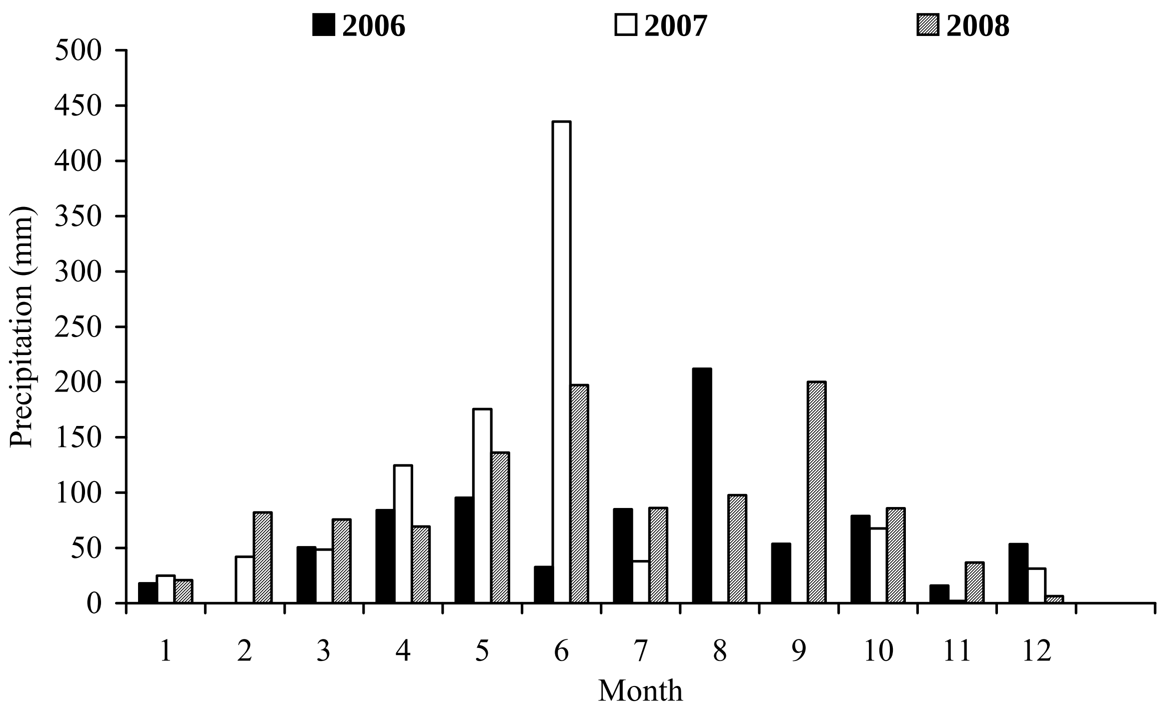


Data acquired from http://www.oznet.ksu.edu/wdl/

Precipitation in 2006 was only 670 mm, so irrigation started early. Irrigation was applied once in June, three times in July, and once in August at a rate of 32 mm per irrigation event for a total application of 160 mm. In 2007, the rainfall total was 770 mm with much of the precipitation occurring in May. Again, there were five irrigation applications for a total of 160 mm (three in July and two in August). In 2008, there was a tornado that destroyed the irrigation system and limited irrigation opportunities early in the growing season. In 2008 precipitation total was nearly 800 mm and supplied adequate moisture until the irrigation unit could be replaced. There were three irrigation applications that all occurred in July for a total application of almost 100 mm. Although the tornado caused additional stress and required soybean replanting, Scandia generally remained close to optimum throughout this study allowing P responses to take place. The combination of precipitation and irrigation would have also created excellent conditions below the surface residue for root growth and nutrient uptake.

The mean annual precipitation at Ottawa is 1000 mm, but Figure 2.19 shows precipitation events are more erratic than at Scandia.

Figure 2.19 Monthly precipitation total for each month in Ottawa (2006-2008).

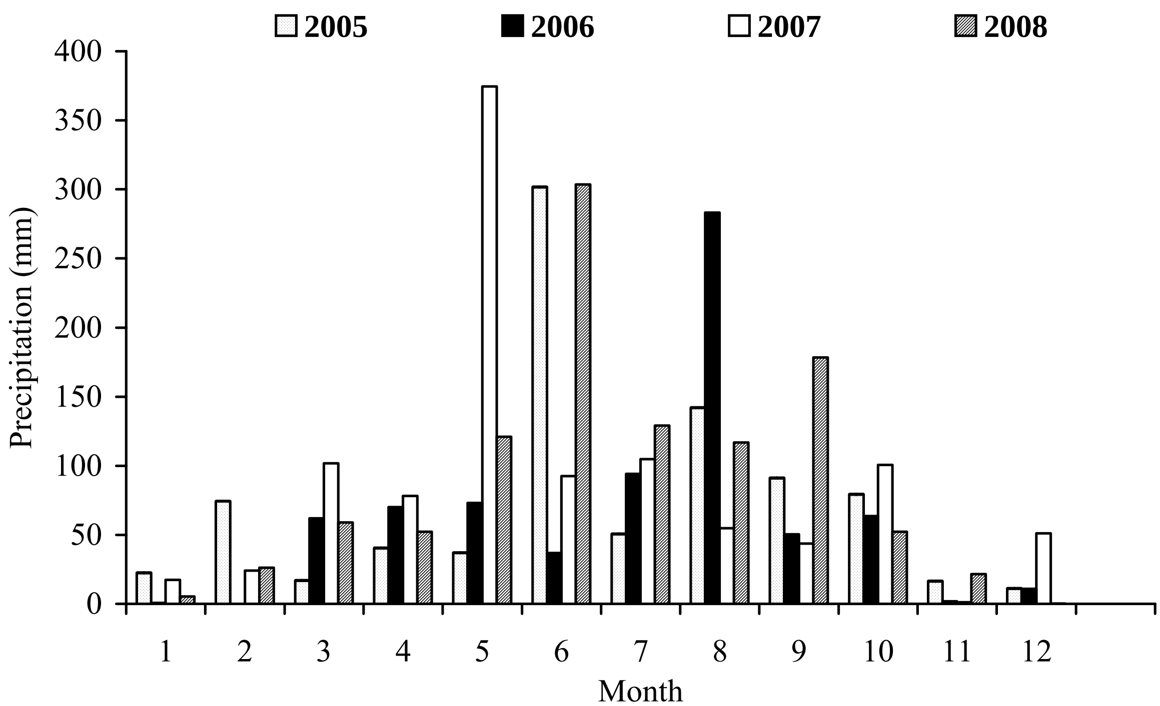


Data acquired from http://www.oznet.ksu.edu/wdl/

In 2006, total precipitation was 780 mm, while 2007 and 2008 were much closer to the mean (990 and 1090, respectively). The low precipitation in 2006 during the first six months probably limited crop productivity early in the season, but higher precipitation later in the season may have positively impacted crop productivity. In 2007, the high precipitation total is the result of receiving 170 mm on the 30th of June. This intense rainfall probably affected the crops by causing saturated soil conditions and resulting crop stress. However, there was very little precipitation after June for biomass and yield productivity. The 2008 crop year was the most 'normal' of the three years as the distribution was not as erratic as the previous two years. The observation from this is that yields were higher in 2008 than previous years.

Precipitation impacts Manhattan more than Scandia and Ottawa because water availability is lower (mean annual precipitation is 880 mm) (Figure 2.20) and both summer and winter crops are grown. As previously seen in Table 2.1, with the high soil test P in the top 7.6 cm and adequate soil test P at the 7.6 to 15 cm depth, a response to P was not expected. However, the opportunity for a response to P could come from extremely rapid growth and nutrient uptake following the relief of crop stress or dry surface conditions by precipitation. But the availability of adequate P and nutrient uptake from deeper in the soil (~15 cm) minimizes that potential. The lack of response in summer crops may have been the result of both high soil test and enough moisture to take up P from throughout the traditional 15 cm tillage zone. Figure 2.20 shows high precipitation in May followed by low precipitation specifically in August and September at Manhattan.

Figure 2.20 Monthly precipitation total for each month in Manhattan (2005-2008).

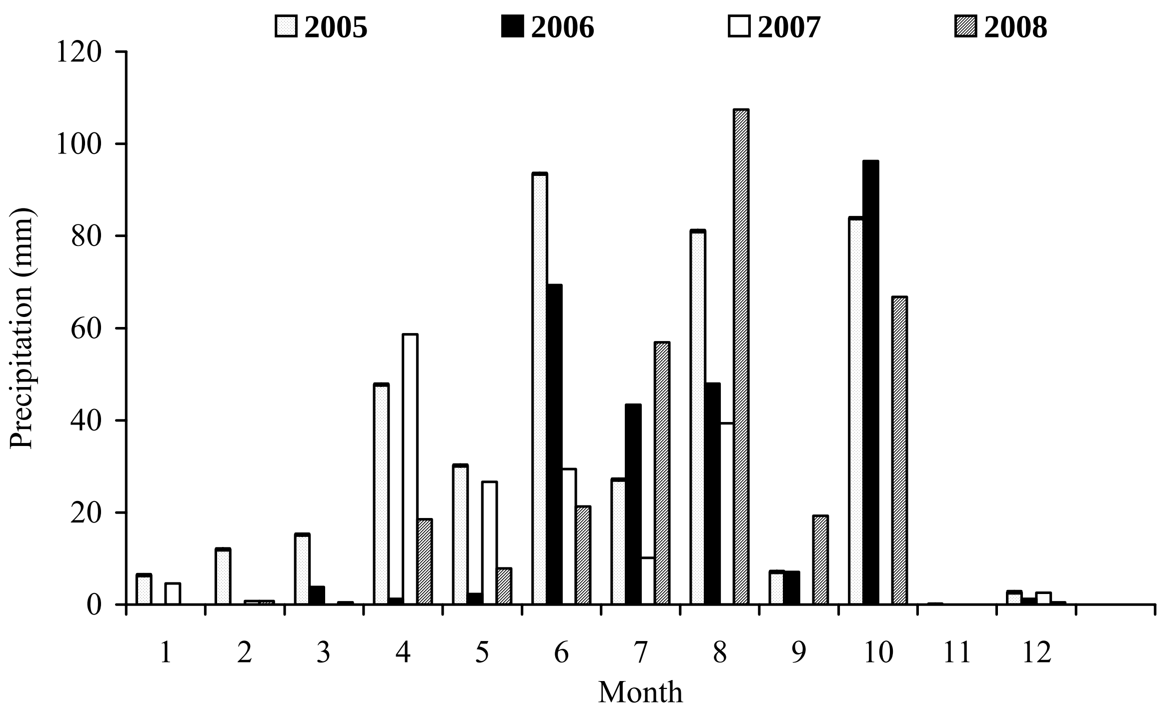


Data acquired from http://www.oznet.ksu.edu/wdl/

The effect of precipitation on wheat would be due to a different portion of the year. Wheat was typically planted in late October (Table 2.1) after the soybean crop was harvested while there was adequate soil moisture. After this time, precipitation decreased dramatically (November through February or March) until spring (Figure 2.20). The 2005-2006 wheat crop was very moisture limited as there was little precipitation in November and December 2005 and no precipitation in January and February 2006. However, rainfall in March occurred just in time to produce surprisingly good yields, but the stress prior to that time likely limited the response to P. The 2006-2007 crop year had minimal precipitation during the winter months, that again probably limited the P response, but did not cause such severe stress as the previous year. In 2008, there was again minimal precipitation over the winter months, but with favorable temperatures and spring growth of wheat.

Tribune annual precipitation total was 440 mm. With the high soil test P level (Table 2.1) and low precipitation, a P response was not expected, which was the outcome of the trial for both wheat and sorghum.

Figure 2.21 Monthly precipitation total for each month at Tribune (2005-2008).



Data acquired from http://www.oznet.ksu.edu/wdl/

Conclusions

All sites in this study had significant vertical P stratification that was attributed to previous years of no-tillage crop production. The low soil test levels at Scandia and Ottawa resulted in crop responses to P that did not occur at the high soil test levels at Manhattan and Tribune. Scandia was the highest yield potential site and that resulted in significant P responses when corn plant samples were evaluated during the vegetative growth. Although there were differences in broadcast or deep band placement or starter effects, they were not consistent.

Corn grain yield responded up to 13.8 kg P ha^{-1} and application of starter fertilizer was important at Scandia. Soybean was not as responsive as corn early in the growing season, but grain yield was increased when P was applied directly to soybean after deep band P was applied on the previous corn crop. The Scandia site is most similar to conditions and data from Iowa and resulted in similar conclusions.

Ottawa results were much different. There was a clear corn response to P in the vegetative growth and P concentration than in grain yield. Similarly, there was limited response in the soybean crop at Ottawa, which did not include yield responses. The lack of response at Ottawa was attributed to increased later season crop stress that probably limited yield more than P uptake. In general, it was clear from the soil test P levels that P application was important at these sites. However, when a response to P was observed, it was at an application rate that was less than half the recommended rate. Since yield production is the primary goal, it should be noted that placement (broadcast or deep) of P did not increase or decrease yields and thus placement options are available without yield reduction. Furthermore, starter application of P appeared to be the most likely P application that would affect yield. Another important conclusion from these sites is that highly productive soybean grown on low soil test P sites need direct fertilization of P to boost yields and maintain or build soil test P levels.

Manhattan and Tribune were much less responsive to P application. At both sites in all crops, consistent responses to P were not found. These sites had high soil test P and a response to P would generally not be expected with the current nutrient recommendation guidelines (Leikam et al., 2003), which was supported by this study. The assumption that water was more available deep in the soil at these dry sites and thus a response to deep applied P may occur even at high soil test P was not found.

The effort to relieve negative effects of stratification through deep band placement of P was not productive, which indicates that stratification of P in these production systems in Kansas may not be as problematic as initially thought. More years of data is needed to make definitive conclusions regarding the effects of precipitation and the long term effects of P placement and rate.

References

Barber, S.A. 1980. Twenty-five years of phosphate and potassium fertilization of a crop rotation. Fertilizer Res. 1:29-36.

Belcher, C. R., and J.L. Ragland. 1972. Phosphorus absorption by sod-planted corn (*Zea mays* L.) from surface-applied phosphorus. Agron. J. 63:754-757.

Bordoli, J.M., and A.P. Mallarino. 1998. Deep and shallow banding of phosphorus andpotassium as alternatives to broadcast fertilization for no-till corn production. Agron. J. 90:27-33.

Bordoli, J.M., and A.P. Mallarino. 2000. P and K placement effects on no-till soybean. Agron. J. 92:380-388.

Borkert, C.M., and S.A. Barber. 1985. Predicting the most efficient phosphorus placement for soybeans. Soil Sci. Soc. Am. J. 49:901-904.

Eckert, D.J. 1985. Review: Effects of reduced tillage on the distribution of soil pH and nutrients in soil profiles. J. Fert. Issues. 2:86-90.

Eckert, D.J., and J.W. Johnson. 1985. Phosphorus fertilization in no-tillage corn production. Agron. J. 77:789-792.

Gordon, W.B., D.L. Fjell, and D.A. Whitney. 1997. Corn hybrid response to starter fertilizer in a no-tillage, dryland environment. J. Prod. Agric. 10:401-404.

Griffith, D.R., J.V. Mannering, and W.C. Moldenhauer. 1977. Conservation tillage in the eastern corn belt. J. Soil Water Conserv. 32:22-28.

Hira, G.G., and N.T. Singh. 1977. Observed and predicted rates of phosphorus diffusion in soils of varying bulk density and water content. Soil Sci. Soc. Am. J. 41:537-540.

Howard, D.D., and M.D. Mullen. 1987. Comparison of surface applied rates of phosphorus and potassium and in-furrow fertilizer solution combinations for no-till corn production. J. Fert. Issues. 4:48-52.

Karathanasis, A.D., and K.L. Wells. 1990. Conservation tillage effects on the potassium status of some Kentucky soils. Soil Sci. Soc. Am. J. 54:800-806.

Karlen, D.L., E.C. Berry, T.S. Colvin, and R.S. Kanwar. 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun. Soil Sci. Plant Anal. 22:1985-2003.

Ketchenson, W.J. 1980. Effect of tillage on fertilizer requirements for corn on a silt loam soil. Agron. J. 72:540-542.

Leikam, D.F., R.E. Lamond, and D.B. Mengel. 2003. Soil test interpretations and fertilizer recommendations. Kansas State University Agricultural Experiment Station. Department of Agronomy. MF-2568.

MacKay, A.D., E.J. Kladivko, S.A. Barber, and D.R. Griffith. 1987. Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci. Soc. Am. J. 51:970-974.

Mahtab, S.K., C.L. Godfrey, A.R. Swoboda, and G.W. Thomas. 1971. Phosphorus diffusion in soils: I. The effect of applied P, clay contant, and water content of soil. Soil Sci. Soc. Am. Proc. 35:393-397.

Mallarino, A.P., J.R. Webb, and A.M. Blackmer. 1991. Corn and soybean yields during 11 years of phosphorus and potassium fertilization on a high-testing soil. J. Prod. Agric. 4:312-317.

Mallarino, A.P., and R. Borges. 2006. Phosphorus and potassium distribution in soil following long-term deep-band fertilization in different tillage systems. Soil Sci. Soc. Am. J. 70:702-707.

Mederski, M.J., and J.M. Wilson. 1960. Relation of soil moisture to ion absorption by corn plants. Soil Sci. Soc. Am. Proc. 35:393-397.

Morrison, J.E., Jr., and F.W. Chichester. 1994. Tillage system effects on soil and plant nutrient distribution on Vertisols. J. Prod. Agric. 7:364-373.

Moschler, W.W., and D.C. Martens. 1975. Nitrogen, phosphorus and potassium requirements in no-tillage and conventionally tilled corn. Soil Sci. Soc. Am. Proc. 39:886-891.

Moscheler, W.W., G.M. Shear, D.C. Martens, G.D. Jones, and R.R. Wilmouth. 1972. Comparative yield and fertilizer efficiency of no-till and conventionally tilled corn. Agron. J. 64:229-231.

Mullen, M.B., and D.D. Howard. 1992. Vertical and horizontal distribution of soil C,N,P,K, and pH in continuousno-tillage corn production. p. 6-10. *In*: M.D. Mullen and B.N. Duck (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Olsen, S.R., W.D. Kemper, and J.C. van Schaik. 1965. Self Diffusion coefficients of phosphorus in soil measured by transcient and steady-state methods. Soil Sci. Soc. Am. Proc. 29:154-158.

Olsen, S.R., F.S. Watanabe, and R.E. Danielson. 1961. Phosphorus absorption by corn roots as affected by moisture and phosphorus concentration. Soil Sci. Soc. Am. Proc. 25:289-294.

Randall, G.W., and R.G. Hoeft. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. J. Prod. Agric. 1:70-79.

Rehm, G.W., S.D. Evans, W.W. Nelson, and G.W. Randall. 1988. Influence of placement of phosphorus and potassium on yield of corn and soybean. J. Fert. Issues. 5:6-13.

Robbins, S.G., and R.D. Voss. Phosphorus and potassium stratification in conservation tillage systems. J. Soil Water Conserv. 46:298-300.

SAS Institute. 2007. The SAS system for windows version 9.1.3. SAS Institute Inc., Cary, NC.

Shear, G.M., and W.W. Moschler. 1969. Continuous corn by the no-tillage and conventional tillage method: A six year comparison. Agron. J. 61:524-526.

Shwab, G.J., D.A. Whitney, G.L. Kilgore, and D.W. Sweeney. 2006. Tillage and phosphorus management effects on crop production in soils with phosphorus stratification. Agron. J. 98:430-435.

Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agron. J. 59240-243.

Toler, J.E., E.C. Murdock, and J.J. Camberato. 2004. Starter fertilizer effects on cotton development and weed interference. J. Cotton Sci. 8:33-41.

Tyler, D.D., and D.D. Howard. 1991. Soil sampling patterns for assessing no-tillage fertilization techniques. J. Fert. Issues. 8:52-56.

CHAPTER 3 - Soil Test Phosphorus in a Vertically and Horizontally Stratified Soil

Abstract

The process of phosphorus (P) stratification after no-tillage crop production and the effects of P placement have not been studied extensively in water limited production systems. This study evaluated the effects of P placement in stratified soils on soil test P distribution and documented both stratification and variability in soil test P in a vertical and horizontal dimension. Four locations were established in 2005 with a range of annual precipitation of 440-1000 mm and initial soil test P levels of 7.6-52.7 mg P kg^{-1} from 0-15 cm depth. Phosphorus fertilizer was applied as broadcast only, deep band only (34.8 kg P ha^{-1} approximately 15 to 20 cm deep directly under the row), in combination with starter (8.7 kg P ha^{-1} starter, and 26.1 kg P ha^{-1} broadcast or deep banded), or as a deep band starter combination with the additional broadcast application of 17.4 kg P ha^{-1} on the rotational soybean (*Glycine max* L. Merr.) crop. Crops were planted directly on top of the applied fertilizer bands. In 2008, soil core samples were collected from directly under the row and in the row middles and were separated into 0-7.6, 7.6-15, 15-23, 23-31,and 31-61cm depth increments from the previous year corn (*Zea mays* L.) or grain sorghum (*Sorghum bicolor* L. Moench) plots. The results showed initial stratification at all sites with enhanced stratification following broadcast P applications, including broadcast applications on soybean. Deep band treatments often resulted in increased P concentration in the deep band zone, while adding starter to the deep band caused a more uniform vertical distribution of P directly under the crop row. Variability in soil test P increased markedly in the deep band treatment at application depth as compared to other portions of the soil. Whether this was due to variability in application or the inability to consistently hit the band area in sampling is not known. But this raises questions as to the applicability of guided sampling programs as a means of sampling fields for fertilizer recommendations where P has been band applied.

Introduction

No-tillage and conventional tillage production practices have been increasing for several years. Trends in U.S. tillage systems show no-tillage acres (defined as planting in an unprepared seedbed) increased from 1.3 million ha (1.6%) in 1972 to 19.4 million ha (16.3%) in 1998 (adapted from Coughenour and Chamala, 2000). Conventionally tilled acres increased from 70.0 million ha in 1972 to 74.5 million ha in 1998, but decreased as a percentage of total cropland from 85.4% to 62.8%, during that time. Benefits of no-till and reduced till production systems include increased soil organic matter (Sainju et al., 2005; Causarano et al., 2006) and the potential for increased nutrient supply via mineralization by microbial biomass (Carter and Rennie, 1982). When no-tillage production systems were first gaining popularity, agronomists and producers became concerned that nutrient stratification would be problematic and would force producers to practice deep tillage periodically to decrease the effects of stratification on nutrient uptake. The word stratification means to form layers, often in the context of rock or sediments. In this application, stratification is the condition by which soil P concentration is layered with the soil surface (0-7.6 cm), P concentration being much greater than lower depths (>7.6 cm). Although conventional tillage provides soil mixing and reduces the severity of stratification as compared to no-tillage (Edwards et al., 1992), the benefits of no-tillage production systems generally outweigh the benefits of uniform nutrient concentrations. Holanda et al. (1998) noted nutrient distribution under conventional tillage regimes is more homogenous than in no-tillage systems because of mixing of soil, crop residues, and fertilizers. Previous studies have documented that increased P content in the surface soil as compared to deep soil layers has changed much more than other nutrients such as potassium (Mallarino and Borges, 2006; Wright et al., 2007). However, Wright et al. (2007) also showed vertical gradients in soil test P concentration persist even when what is now considered conventional tillage, chisel plow, methods are employed.

Strip tillage (no-tillage zone between tilled strips) has been used to combine some benefits of no-tillage production systems with the benefits of conventional systems. Some of the benefits of strip tillage include: soil conservation, a warmer seedbed to promote early season seedling growth in cool climates, and the ability to place fertilizer in a band deep in the soil. The difficulty of this fertilizer placement method, or any method that places fertilizer in a band, is that soil sampling and soil test interpretation becomes difficult. Some research suggested soil sampling in a vertically and laterally stratified soil should be based on the knowledge of band locations (Kitchen et al., 1990; Robbins and Voss, 1991; Howard et al., 1999; Borges and Mallarino, 2001), while others recommend random soil sampling for evaluating the nutrient status of these soils (Tyler and Howard, 1991).

Most previous work on nutrient stratification has been done in humid climates where moisture availability and rainfall distribution was plentiful than the western Great Plains region. Mackay and Barber (1985) discussed in detail the impacts of soil moisture on P uptake and root growth. They further cite the work of Olsen et al. (1961), who reported an eight fold decrease in P diffusion, when soil moisture decreased by a factor of two. Mackay and Barber (1985) also describe that with an increase in soil moisture, effective diffusion increases as there is a more direct and shorter pathway for diffusion of P through the soil. Other studies (Singh et al., 1966; Belcher and Ragland, 1972; Moschler and Martens, 1975) have focused on fertilizer placement and conclude that when there is sufficient rainfall in a growing season to maintain root activity in the surface soil, nutrient stratification has minimal negative effects and in some cases benefits nutrient uptake of corn.

The premise of this study was based on the logic of Mackay and Barber (1985) that with the importance of soil moisture in P diffusion, P placement in regions with limited soil moisture may help overcome potential limitations on P uptake created by nutrient stratification. The objectives of this segment of the study were to document the extent of vertical and horizontal stratification of soil P from starter fertilizer, broadcast, and deep band applied P and to document the variability in soil P concentration in broadcast and deep band application techniques. The hypothesis was that broadcast application of P will increase vertical stratification and band application will increase lateral stratification and soil test P variability. These findings should help in identifying appropriate soil sampling techniques in nutrient stratified environments with varying soil moisture.

Materials and Methods

Four sites across Kansas were established in the spring of 2005. The Scandia site is located west of Scandia, KS at the KSU Agronomy North Central Kansas Irrigation Experiment Field (39°46′23″ N lat.; 97°47′19″ W long.). The soil is classified as a Crete silt loam (fine, smectitic, mesic Pachic Argiustolls). The Ottawa site is located south of Ottawa, KS at the KSU Agronomy East Central Experiment field (38°32′19″ N lat.; 95°15′11″ W long.). The soil at this site is classified as a Woodson silt loam (fine, montmorillonitic, thermic, Abruptic Argiaquoll). The Manhattan site is located in Manhattan, KS at the KSU Agronomy North Farm (39°08′02″ N lat.; 96°37′09″ W long.). The soil is classified as a Smolan silt loam (fine, smectitic, mesic Pachic Argiustolls). The Tribune site is located west of Tribune, KS at the Western Kansas Research and Extension Center (38°28′03″ N lat.; 101°46′03″ W long.). The soil at this site is classified as a Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls). The 30-year mean annual rainfall totals for these sites are 1000, 880, 710 and 440 mm for Ottawa, Manhattan, Scandia and Tribune respectively (http://countrystudies.us, accessed 8/2008). All sites are rainfed except Scandia, which received supplemental irrigation.

The Scandia and Ottawa sites had a corn-soybean rotation; the Manhattan site had a winter wheat (*Triticum aestivum* L.)-grain sorghum-soybean rotation, and the Tribune site had a winter wheat-grain sorghum-fallow rotation. Appropriate rotations common to the area were used at each location with each crop present in the rotation each year. All sites had a history of no-till crop production for greater than 5 years when the experiments were initiated.

At the onset of this study, all sites were soil sampled for P concentration with random samples from each replication. A hydraulic probe 3.8 cm in diameter was used to take 10-15 core samples to a depth of 91 cm from each block. Each core was separated into 0-7.6, 7.6-15, 15-23, 23-31, and 31-61 cm depth increments. The core segments were then combined by depth from each block to provide composite samples by depth for each replication within each crop. These samples were analyzed for P content with a Lachat Quickchem 8000 using the Mehlich 3 extractant (Frank et al., 1998; Mehlich, 1984).

A randomized complete block design was used at each site with three or four replications. Twelve treatments consisting of combinations of P rate and method of application, previously described in Chapter 2 were applied, in 2006 through 2008. Six treatments were sampled in the spring of 2008 to determine the effect of P application on soil test levels, including:

0 kg P ha^{-1} (Check)

34.8 kg P ha^{-1} broadcast (BDCST)

26.1 kg P ha^{-1} broadcast and 8.7 kg P ha^{-1} starter combination (BDCST+ST)

34.8 kg P ha^{-1} deep band (BND)

26.1 kg P ha^{-1} deep band and 8.7 kg P ha^{-1} starter combination (BND+ST)

26.1 kg P ha^{-1} deep band and 8.7 kg P ha^{-1} starter applied to corn with an additional 17.4 kg P ha^{-1} broadcast on soybean (BND+ST+SOY)

Crops were no-till planted in 76 cm rows for row crops and 19 cm rows for drilled crops (wheat). Starter fertilizer was applied 5 cm to the side and 5 cm below the seed on row crops and was applied with the seed in wheat. Broadcast application was always applied on the soil surface just prior to planting with a drop-type spreader or hand-applied. Deep band treatments were applied with a strip till unit at about 15 cm deep in row crops (except sorghum at Tribune). In winter wheat, a coulter applicator on 38 cm spacing was used to apply the P as deep as possible (~10 cm). Due to moisture limited conditions and potential excessive soil drying from strip till operations, strip tilling was only done in year one at Tribune. Deep application of P at Tribune was accomplished using a coulter applicator for all crops (on 38 cm spacing). Forms of P fertilizer used were ammonium polyphosphate (10-34-0) or triple superphosphate (0-46-0). Appropriate nitrogen application rates were used and balanced so all treatments received the same nitrogen rates at each location and thus effects due to nitrogen were eliminated. Each crop was harvested and grain was collected for yield calculation and nutrient analysis. The grain was ground and analyzed for total P content using a sulfuric acid and hydrogen peroxide digest and colormetric analysis (Thomas et al., 1967).

In the spring of 2008, intensive soil samples were taken to determine the P concentration in all plots except BDCST, which was sampled in the summer of 2008. A 2.5 cm probe was used to sample plots that were corn or grain sorghum in the 2007 growing season. Samples were taken to depths of 0-7.6, 7.6-15, 15-23, 23-31, and 31-61 cm. Fifteen soil cores at each depth were taken from directly under the crop row and combined as a composite sample from each individual plot. This was repeated directly between the crop rows for the same depths. These samples were then analyzed for Mechlich 3 extractable P using the aforementioned procedures.

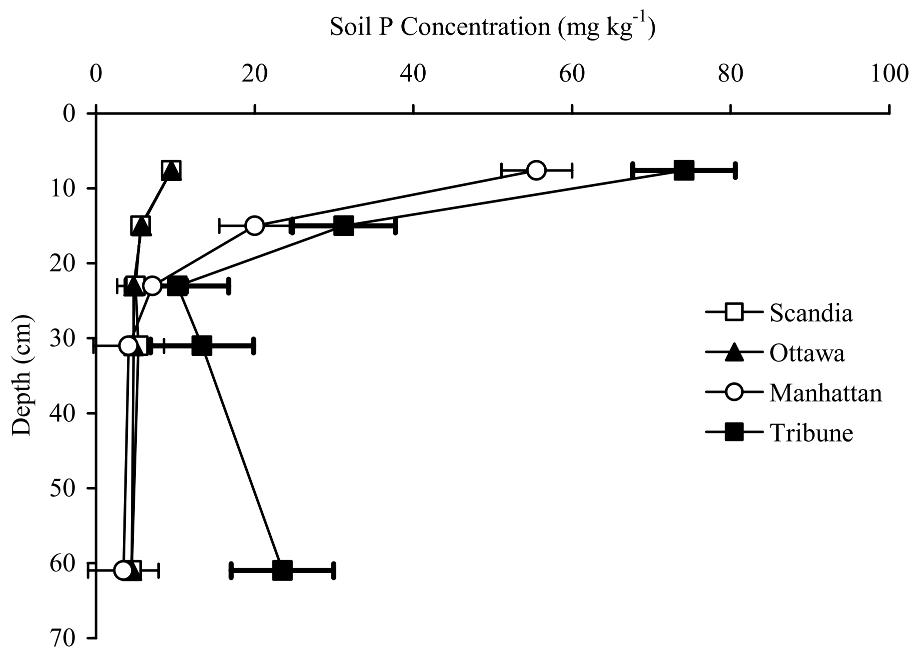
Data was statistically analyzed using SAS *proc mixed* or *proc glm*. To conservatively assess significant differences in *proc mixed*, p-values were adjusted using the Scheffé procedure. The mean, minimum, maximum, and coefficient of variation (CV) of Mehlich 3 P was calculated for the check, BDCST, and BND treatments using SAS *Proc means* (SAS, 2007). Confidence limits (95%) were placed on soil test P data for each site, location (row versus row middle), treatment, and depth. Based on this evaluation, individual plots that fell outside the 95% confidence limits for that treatment or depth were re-sampled in the summer of 2008 at the 0-7.6 and 7.6 to 15 cm depth. This resulted in replacing 19 of 75 data points (the remaining 56 data points were not improved by resampling over the original dataset) that fell outside the 95% confidence limits because there was an improvement in the estimate of the mean value and resulted in a clearer interpretation.

Results and Discussion

Initial Soil Test Levels in 2005

Initial soil test P data from each site taken at the onset of this experiment in 2005 are displayed in Figure 3.1.

Figure 3.1 Mean soil test P concentration (mg kg^{-1}) for Scandia, Ottawa, Manhattan, and Tribune at five depths showing the presence of stratification at the onset of this experiment. Error bars represent the standard error of P concentration for each site.



Error bars represent the standard error of the mean

All sites had surface (0-7.6 cm) P concentrations significantly greater than all other depths at $p<0.05$, confirming stratification. Two sites, Ottawa and Scandia had very low initial surface (0-7.6 cm) P concentrations considered deficient or responsive by KSU fertilizer recommendations (Leikam et al., 2003), while the Manhattan and Tribune sites had high initial surface P concentrations and would therefore be considered adequate to support crop production, or non-responsive. The next lower sampling depth (7.6 -15 cm) for all sites showed P concentration decreased markedly as compared to the surface.

Phosphorus fertilizer recommendations in Kansas are made from samples collected from the top 15 cm of soil (Leikam et al., 2003). Averaging the top two sampled depths, the initial soil P concentrations in the surface 15 cm of soil were 7.6, 7.6, 37.8, and 52.7 mg P kg^{-1} soil for

Scandia, Ottawa, Manhattan, and Tribune, respectively, with the Scandia and Ottawa sites considered responsive and the Manhattan and Tribune sites considered non-responsive. The soil at the Manhattan and Tribune sites did not reach the responsive range until the 15 to 23 cm depth. Therefore, Ottawa and Scandia are the only sites where a response to P fertilizer was expected and are the only sites that would normally receive a P recommendation using the traditional nutrient sufficiency fertilizer recommendations. The KSU nutrient sufficiency recommendation (Leikam et al., 2003) is calculated with the following equation:

P Recommendation = [50+(Yield*0.2)+(P*-0.25)+(Yield*P*-0.01)]

Where Yield is the expected yield in bushels per acre, and P is the soil test P concentration in ppm, and P recommendation is in pounds P_2O_5 per acre

Therefore, with an expected corn grain yield for Scandia set at 13,800 kg ha^{-1}, the calculated P recommendation would be 22.5 kg P ha^{-1}. Likewise, if the Ottawa corn grain yield goal was set at 7,500 kg ha^{-1}, the P recommendation would be 17.9 kg P ha^{-1}. Both the Manhattan and Tribune sites would not receive a P recommendation for any yield level of corn, wheat, soybean or sorghum.

Changes in Soil Test Levels over time

Samples taken in 2008 had similar significant differences in soil P concentration as those taken in 2005 with depth ($p<0.01$) Additionally, significant differences in horizontal distribution were found for 2008 samples taken from the crop row and row middles, likely in part as a result of fertilizer application practices ($p=0.06$). Phosphorus concentration (mg P kg^{-1} soil) differences due to depth or treatment were compared using a protected LSD and are reported in Table 3.1.

Table 3.1 Soil test P means (mg kg^{-1}) and significant differences (using LSD) at all sites and depths for samples taken in row and row middles. Treatments include treatment 1 (check), 7 (BDCST), 8 (BDCST+ST), 9 (BND), 10 (BND+ST), 12 (BND+ST+SOY).

	----------------------Row Middle (Treatment) ----------------------							---------------------------Row (Treatment)---------------------------						
Depth (cm)	1	7	8	9	10	12	LSD†	1	7	8	9	10	12	LSD†
	-----Scandia-----													
0-7.6	8.5	10.0	15.0	7.5	10.5	11.3	2.5	11.5	16.5	40.5	9.0	17.8	21.5	9.6
7.6-15	6.0	5.5	7.3	5.8	6.0	6.3	NS	6.0	6.5	12.5	18.0	24.8	7.3	10.9
15-23	3.8	4.5	5.5	3.5	5.0	4.3	NS	5.0	6.5	6.8	8.8	39.8	4.8	NS
23-31	2.8	-	3.5	2.5	3.0	3.0	NS	3.5	-	4.3	3.3	6.0	3.0	1.6
31-61	4.0	-	6.3	6.0	4.3	8.3	NS	4.5	-	4.8	3.0	4.3	3.5	NS
LSD*	1.2	2.7	2.2	2.9	1.2	1.9		3.8	4.5	8.1	8.5	NS	2.4	
	-----Ottawa-----													
0-7.6	11.5	7.8	12.0	8.8	11.3	10.8	NS	11.3	7.8	20.8	15.5	29.0	31.8	12.4
7.6-15	5.3	3.5	6.0	4.3	10.3	4.8	NS	5.3	3.5	9.0	17.3	43.8	11.8	16.1
15-23	3.0	3.0	3.8	2.5	3.3	5.3	NS	3.3	3.0	3.8	3.8	5.8	3.8	1.2
23-31	2.8	-	3.0	2.3	3.0	3.3	NS	2.5	-	3.0	2.5	3.3	4.0	1.0
31-61	2.3	-	2.5	2.3	2.3	2.5	NS	2.0	-	3.0	2.0	4.0	2.3	2.0
LSD*	2.2	0.9	1.9	0.9	4.9	4.2		1.5	1.7	4.2	8.4	14.5	11.3	
	-----Manhattan-----													
0-7.6	55.0	73.3	56.0	47.7	45.3	54.0	10.7	49.0	77.0	67.0	48.0	43.3	69.0	15.5
7.6-15	33.0	42.3	16.0	21.7	22.7	18.3	14.0	32.3	28.0	18.3	75.3	45.0	32.3	26.3
15-23	11.7	25.33	7.7	19.3	8.7	8.0	8.7	7.3	24.7	5.7	27.7	18.7	11.0	NS
23-31	5.0	-	3.3	6.0	4.3	4.7	NS	7.0	-	4.7	9.3	6.7	4.0	NS
31-61	4.3	-	3.3	5.3	5.7	4.0	NS	4.7	-	5.0	4.3	4.0	3.7	NS
LSD*	14.7	13.8	12.6	8.5	12.4	6.8		13.6	6.6	13.1	33.2	13.3	8.5	
	-----Tribune-----													

0-7.6	60.0	-	66.0	63.0	54.5	-	NS	44.8		74.5	64.5	65.0	-	NS
7.6-15	15.3	-	19.0	14.3	15.0	-	NS	13.0		21.0	15.8	27.0	-	NS
15-23	11.3	-	9.3	8.5	11.8	-	NS	10.3		10.8	9.5	11.5	-	NS
23-31	11.5	-	12.8	11.3	11.5	-	NS	12.0	-	14.0	11.8	13.3	-	NS
31-61	19.5	-	21.8	24.0	26.3	-	NS	19.8	-	22.3	21.3	22.5	-	NS
LSD*	17.24		10.51	9.00	8.10	-		11.44		11.47	17.75	27.78	-	

†=Protected LSD; NS=not significant

Data in superscript is from resampling.

Treatment 1=true check; Treatment 7=34.8 kg P ha^{-1} broadcast; Treatment 8=8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} broadcast; Treatment 9=34.8 kg P ha^{-1} deep band; Treatment 10=8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} deep band; Treatment 12=8.7 kg P ha^{-1} starter, 26.1 kg P ha^{-1} deep band and 17.4 kg P ha^{-1} broadcast on soybean

Calculated using *Proc glm* (alpha=0.1, SAS, 2007)

At all four sites, it is clear there is still a significant stratification in P concentration in the check plot where no P was applied. This stratification was seen in both the crop row and the row middles. Although stratification was seen in the row middles, two sites had treatments that did not follow this trend. For the row middles, all sites had a significant decrease in P concentration from the 0-7.6 cm depth to the 7.6-15 cm depth except the BND treatment at Scandia and the BND+ST treatment at Ottawa. The mean P concentration in both treatments decreased in the 7.6-15 cm depth, but were not significantly different from the surface layer.

When evaluating samples taken from within the crop row, variability, as indicated by a high LSD, is readily apparent. These plots illustrate some of the challenges of variability in soil testing in fields where P has been banded, which were also found by Mallarino (1996) and Cox et al. (2003). In the check and broadcast treatments, P concentration decreases with depth, similar to what is seen in the row middles. However, where P was deep banded, soil test P concentrations do not show a significant decrease with depth and in some cases show an increase. When P was deep banded, the concentration was greater at the 7.6-15 cm depth than where it was broadcast except for the Tribune site. This indicated a higher availability of P at lower soil depths in the row area. The Tribune site probably did not increase in P concentration because of the high initial P concentration and the inability to apply the P fertilizer as deep as other sites since a coulter applicator was used to apply the deep band treatment. The coulter application at Tribune was also spaced at 38 cm rather than the 76 cm spacing used in other row crops, which caused a one-half rate to be applied in twice the number of bands.

The P concentration in the 7.6-15 cm depth from the BND+ST treatment was significantly higher than all other depths at Ottawa. This same treatment at Scandia and Manhattan produced a higher mean P concentration in the 7.6-15 cm and 15-23 cm depths, but was not significantly different due to variability in soil test P. At Tribune, the 7.6-15 cm depth from the BND+ST treatment was significantly lower in P concentration than the 0-7.6 cm depth, which was likely the result of coulter application on 38 cm spacing.

In addition to depth, P treatments were evaluated. Changes due to treatment in the row middles were only significant at Scandia and Manhattan. The 0-7.6 cm depth with the BDCST+ST and the BND+ST+SOY treatments at Scandia and the BDCST treatment at Manhattan were the only treatments that had a significantly higher P concentration than the check. These treatments all included broadcast P application, which caused the soil test P increase in the 0-7.6 cm depth.

Treatment differences from samples taken from the crop row revealed that two of four sites (Scandia and Ottawa) had significantly higher soil test P at the 0-7.6 cm depth in the BND+ST+SOY treatment than the check, while the Manhattan site, although higher, was not statistically significant. This treatment at the Manhattan site was probably not significant because of the high initial soil test P level. The BND+ST at Scandia and Ottawa, had significantly higher soil test P at the 7.6-15 cm depth than the check, but the surface 0-7.6 cm concentration only significantly increased at Ottawa. Again, at Manhattan and Tribune, this treatment was not significantly different from the check. For the BND treatment, Scandia and Manhattan were significantly higher than the check in the 7.6 to 15 cm depth. All other sites were unchanged by the application of P deep in the soil. When P was applied as a starter and broadcast combination (BDCST+ST), the Scandia and Manhattan sites had significantly higher P concentrations at the 0-7.6 cm depth while the Manhattan site was the only site that was significantly affected by the application of the BDCST treatment.

One other primary objective of this study was to determine if the application of P at a specific depth influenced the soil test P concentration as compared to another depth. To accomplish this, P application methods were grouped according to the primary placement method. The BDCST and BDCST+ST treatments were grouped as broadcast, while the BND and BND+ST treatments were grouped as deep band. This data was then evaluated for the depths where P was applied, 0-7.6 cm and 7.6 to 15 cm depth (Table 3.2).

Table 3.2 Phosphorus concentration (mg kg^{-1}) for combined broadcast and deep band treatments at the 7.6 and 15 cm depths.

	---Row Middle---			---Row---		
Depth (cm)	Broadcast	Deep Band	LSD†	Broadcast	Deep Band	LSD†
	---Scandia---					
0-7.6	12.5	9.0	2.74	28.5	13.4	12.13
7.6-15	6.4	5.9	NS	9.5	21.4	9.72
	---Ottawa---					
0-7.6	10.9	10.0	NS	14.3	22.3	NS
7.6-15	4.8	7.3	NS	6.3	30.5	16.58
	---Manhattan---					
0-7.6	64.7	46.5	9.16	72.0	45.7	12.09
7.6-15	29.2	22.2	NS	23.2	60.2	23.22
	---Tribune---					
0-7.6	66.0	58.8	NS	74.5	64.8	NS
7.6-15	19.0	14.6	NS	21.0	21.38	NS

†=Protected LSD; NS=not significant
Calculated using *Proc glm* (alpha=0.1, SAS, 2007)

Data from the row middles showed the only significant difference between broadcast and deep band was at the 0-7.6 cm depth at the Scandia and Manhattan sites in which the broadcast treatments were significantly higher (Table 3.2). Samples from the row displayed more differences. At the shallow depth (0-7.6 cm), the Scandia and Manhattan sites had higher P concentration in the broadcast than deep band, while the Ottawa and Tribune sites were not different. When looking at the next depth (7.6-15 cm), all sites except Tribune had higher P concentrations in the deep band than the broadcast treatments. This analysis led to the conclusion that P application at a specific soil depth can generally be confirmed by increased soil test P.

Variability and Uncertainty in Soil Test P

As the data collected in this study was processed, it was clear that some expected differences were not significant because of variable concentrations of P in the soil, or our inability to adequately sample those plots which had been band applied. To evaluate the effect of placement on the soil test P variability, the mean, minimum, maximum, and CV of soil test P was calculated using *proc means* (SAS 2007) and reported in Table 3.3.

Table 3.3 Mean, minimum, maximum (mg P kg^{-1}), and CV of soil test P at the 0-7.6, 7.6-15, and 0-15 cm depth for treatments 1 (Check), 7 (BDCST), and 9 (BND) in the row and row middles at Scandia, Ottawa, and Manhattan.

	Treatment 1				Treatment 7				Treatment 9			
Depth (cm)	Mean	Min	Max	CV (%)	Mean	Min	Max	CV (%)	Mean	Min	Max	CV (%)
	Scandia (Row Middle)											
0-7.6	8.5	7.0	11.0	20.4	10.0	7.0	13.0	29.4	7.5	6.0	9.0	17.2
7.6-15	6.0	5.0	7.0	13.6	5.5	5.0	7.0	18.2	5.8	5.0	6.0	8.7
0-15	7.3	5.0	11.0	25.3	7.8	5.0	13.0	40.7	6.6	5.0	9.0	19.7
	Scandia (Row)											
0-7.6	11.5	7.0	23.0	66.8	16.5	11.0	24.0	33.0	9.0	8.0	10.0	9.1
7.6-15	6.0	5.0	8.0	23.6	6.5	5.0	8.0	19.9	18.0	6.0	41.0	86.9
0-15	8.8	5.0	23.0	67.4	11.5	5.0	24.0	56.4	13.5	6.0	41.0	83.9
	Ottawa (Row Middle)											
0-7.6	11.5	8.0	16.0	32.1	7.8	6.0	9.0	16.2	8.8	7.0	11.0	19.5
7.6-15	5.3	5.0	6.0	9.5	3.5	3.0	4.0	16.5	4.3	3.0	5.0	22.5
0-15	8.4	5.0	16.0	49.4	5.6	3.0	9.0	43.5	6.5	3.0	11.0	41.9
	Ottawa (Row)											
0-7.6	11.3	9.0	14.0	18.3	7.8	6.0	11.0	30.5	15.5	11.0	19.0	22.0
7.6-15	5.25	4.0	7.0	28.6	3.5	3.0	4.0	16.5	17.25	6.0	39.0	85.8
0-15	8.25	4.0	14.0	43.8	5.6	3.0	11.0	49.3	16.4	6.0	39.0	61.0
	Manhattan (Row Middle)											
0-7.6	55.0	29.0	69.0	41.0	73.3	55.0	89.0	23.4	47.7	34.0	56.0	25.0
7.6-15	33.0	14.0	46.0	51.0	42.3	21.0	56.0	44.2	21.7	12.0	28.0	39.3
0-15	44.3	13.0	76.0	58.6	57.8	21.0	89.0	40.4	37.8	12.0	64.0	52.6
	Manhattan (Row)											
0-7.6	49.0	30.0	65.0	36.1	77.0	56.0	93.0	24.7	48.0	31.0	62.0	32.7
7.6-15	32.3	12.0	49.0	58.1	28.0	13.0	36.0	46.4	75.3	36.0	100.0	45.7

0-15	40.7	12.0	65.0	46.0	52.5	13.0	93.0	58.2	61.7	14.0	88.0	69.0

Treatment 1=true check; Treatment 7=34.8 kg P ha^{-1} broadcast; Treatment 9=34.8 kg P ha^{-1} deep band
Calculated using *Proc means* (SAS, 2007)

Proc mixed was then used to evaluate the effects of each treatment (check, BDCST, and BND), depth (0-7.6, 7.6-15, and the two combined as 0-15), and the location (row and row middle) the sample was taken on the CV of soil test P. From this analysis, all treatment by depth combinations from the row middles had statistically similar CV's. Likewise, when row middle samples were compared to samples from the row, the CV's were statistically similar. There were two important significant differences. First is that the BDCST treatment sample from the row had a lower CV than the BND treatment sample at the 7.6-15 cm depth ($p<0.05$). Second, the 0-7.6 cm depth of the BND treatment from the row had a significantly lower CV than the 7.6-15 cm depth ($p=0.05$). The 0-15 cm combination generally resulted in CV's that were as high or higher than the most variable individual depth.

When P was applied as a broadcast treatment, the variation in soil test P was not different depending on sampling location (row or row middle) because it was spread uniformly over the entire soil surface. The 0-7.6 cm depth CV of the broadcast treatment was also similar to the other depths because of the dilution effects of spreading the P over the entire soil surface.

The deep band treatment had a very small concentrated band of P fertilizer, which allowed for increased variability because of the decreased likelihood of extracting a sample from the band. If a sample was taken from the band, it resulted in an extremely high P concentration, but if the sample was not taken from the band, a much lower P concentration was the result. If the sample was always taken from the previous fertilizer band, the CV would likely decrease. Similarly, if P fertilizer was placed in a deep band configuration in generally the same area year to year, this would cause a wider or larger fertilized zone, thereby increasing the likelihood of sampling within that zone. The ability to get a good estimate of soil test P should also increase over time with this application.

Phosphorus Balance and Lowering Soil Test Phosphorus Over Time

Phosphorus application rates, crop yield, and P removed have dramatic effects on P soil test balance. Table 3.4 contains P removed in the grain for each crop and location.

Table 3.4 Phosphorus balance calculation using P application totals for the rotation and grain P (kg ha^{-1}) removed for each rotation (calculated using 2007 and 2008 data at Scandia, Ottawa, and Tribune and 2008 data at Manhattan).

	P Application (kg P ha^{-1})				
	0	8.7	17.4	34.8	52.2
	Scandia				
Corn P Removal (kg P ha^{-1})	29.0 b	36.7 a	37.1 a	37.9 a	38.8 a
Soybean P Removal (kg P ha^{-1})	17.1 c	18.5 bc	18.8 b	20.5 a	20.8 a
Balance (application-removal)	-46.1	-46.5	-38.5	-23.6	-7.4
	Ottawa				
Corn P Removal (kg P ha^{-1})	15.8 c	18.0 b	20.9 a	21.0 a	21.5 a
Soybean P Removal (kg P ha^{-1})	10.0 c	11.4 b	11.4 b	13.0 a	12.4 ab
Balance	-25.8	-20.7	-14.9	0.8	18.3
	P Application (kg P ha^{-1})				
	0	17.4	34.8	69.6	109.6
	Manhattan				
Wheat P Removal (kg P ha^{-1})	10.5 b	14.5 a	13.5 a	14.4 a	12.7 a
Sorghum P Removal (kg P ha^{-1})	19.9 a	17.1 a	18.6 a	17.9 a	18.5 a
Soybean P Removal (kg P ha^{-1})	23.0 a	24.8 a	23.6 a	23.7 a	25.7a
Balance	-53.4	-39.0	-20.9	13.6	52.7
	Tribune				
Wheat P Removal (kg P ha^{-1})	11.3 a	11.5 a	11.0 a	11.7 a	
Sorghum P Removal (kg P ha^{-1})	14.0 a	14.8 a	13.0 a	13.6a	
Fallow P Removal (kg P ha^{-1})	0	0	0	0	
Balance	-25.3	-8.9	10.8	44.3	

Letters indicate significant differences in P removal over different P application totals (alpha=0.1, *proc glm*, SAS 2007)

The data included in Table 3.4 includes 2007 and 2008 P removal data at Scandia, Ottawa, and Tribune. At Manhattan, only 2008 data was used because the three-year rotation of applied P was not complete until 2008. The yield potential of these sites for any given crop highest to lowest was Scandia, Ottawa, Manhattan, and Tribune. As the data in Table 3.4 shows, all levels of application for the rotation at Scandia resulted in a net negative P balance. This means that over time, even at the highest applications of P, soil test P levels would slowly decrease at this site. Grain P removal rates were significantly higher for any level of application than the check in corn at Scandia and became significant above the check at 17.4 kg P ha^{-1} application and 34.8 kg P ha^{-1} application in soybean (Table 3.4). Ottawa grain P removal showed similar results as the P removed in the grain increased with application rate (Table 3.4). However, since Ottawa is a lower yielding site, a positive P balance was reached when 34.8 kg P ha^{-1} was applied. Any lower application resulted in a negative balance indicating greater P removal than application. The Manhattan rotation included three crops and therefore had different application rates coupled with removal from an additional crop. Manhattan grain P removal in wheat increased with P application, but sorghum and soybean were not affected (Table 3.4). The P balance at given application rates showed that a positive balance was achieved at 69.6 kg P ha^{-1} applied over a three year period. The Tribune site only had four application rates because soybean was not included in the rotation (Table 3.4). There were no differences in P removal in the grain at Tribune, but a net negative balance occurred until application of 34.8 kg P ha^{-1} per three years.

It typically takes about 8.8 kg P ha^{-1} to change the soil test P one mg kg^{-1} on silt loam soils in Kansas (Leikam et al., 2003). Using this buffer factor, the change in soil test P can be calculated from Table 3.4. When no P was applied, the soil test P would annually decrease by 2.6, 1.5, 2.0, and 1.0 mg P kg^{-1} at Scandia, Ottawa, Manhattan, and Tribune, respectively. At the highest rate of application, Scandia would still decrease soil test P by 0.4 mg P kg^{-1} annually. The other sites, Ottawa, Manhattan, and Tribune would annually increase soil test P by 1.1, 3.0

and 2.5 mg P kg^{-1}, respectively. So, even at the highest rate used in this study, Scandia soil test P should continue to decline over time. At Ottawa, using the initial soil test of 7.6 mg P kg^{-1} (mean soil test for 0-15 cm) and the highest application rate (52.2 kg P ha^{-1}) it would take approximately 11 years to build the soil test to the critical level of 20 mg P kg^{-1}. Alternatively, the Manhattan and Tribune sites have such a high soil test P level, these rotations could be grown for almost nine years at Manhattan (calculated with initial soil test P of 37.8 for 0-15 cm) and about 33 years at Tribune (calculated using initial soil test P of 52.7 for 0-15 cm) before drawing the soil test P down to 20 mg P kg^{-1}.

The discussion in this section results in two very important outcomes: 1) low soil testing, high yielding sites need adequate P fertilization in all crops to both maintain a positive P balance and build soil test P and 2) high soil test P sites with a moderate or low yield potential can produce crops for many years without P fertilization and maintain soil test P above the critical level.

Conclusions

Phosphorus concentration in stratified soils is altered by placement and can be difficult to assess. When P fertilizer was applied broadcast in a no-till or strip tilled soil, soil test P concentrations were similar regardless if the samples were taken from the row or row middles. Depending on the P application rate and crop removal levels, P stratification will likely continue or become more exaggerated with broadcast application. Deep banding P under the row in a strip-till system has little impact on soil P concentration in the row middles, but does change the distribution of P in the crop row area (when the sample is taken from the band). Generally, an increased P concentration in the band zone (7.6-15 cm) and a comparatively lower concentration of P in the surface (0-7.6cm) soil was found with deep banding. The starter combination with deep band resulted in a somewhat more even distribution of P in the soil causing the surface and 7.6-15 cm depths to be similar in most cases. When P was broadcast on soybean with a starter and deep band combination on the previous crop, it forced the surface P concentration to be significantly higher than at other depths.

This study additionally showed that soil testing for P in the row could detect if a deep band was applied by resulting higher P concentrations in the 7.6-15 cm depth as compared to the surface concentrations. However, there was often considerable variability in soil test P in banded areas, likely as a result of not consistently sampling banded areas. This variability was a challenge throughout this study, and was a result of vertical stratification (probably caused by long-term no-tillage) and lateral stratification caused by P application in bands. The data shows that when attempting to take samples from the deep band zone, the variability (CV of soil test P) severely increases. However, when samples were taken from other portions of the soil (other depths or row middles), the variability was relatively lower. When plot P concentrations fell outside the 95% confidence limits for that treatment, plots from three of the sites were re-sampled. However, only 25% of those re-samples improved the confidence of the plot mean. Although variability has been a large portion (problem) in this study, it may be one of the most important findings. In vertically and laterally stratified soil, soil test P variability and the probability that a soil sample will be taken from the intended zone and result in 'quality' data is not only a problem in meticulously managed research plots but will be a colossal problem in producer situations.

Finally, the importance of P management and fertilization, particularly at low soil test levels was noted. Low soil testing, highly productive sites need P fertilization or soil test P will decline and have an even greater influence on yield. In these high yielding, high P removal situations, building soil test P will be a challenge that will take considerable time to achieve. However, the alternative is true for lower yielding sites with high soil test P. Here, P fertilization is not an appropriate economic, agronomic, or environmental decision. In these sites, crops can be grown for years without P fertilization while obtaining maximum yield.

These findings question the recommendation of directed soil sampling from the banded area to generate soil test P recommendations. The high degree of variability (CV's range from 8.7% to 86.9% in the deep band treatment/zone), is similar to variability found by others (Sawchik and Mallarino, 2008; Cambardella et al., 1994; Wollendaupt et al., 1994; Mallarino, 1996; Nolin et al., 2000; Cox et al., 2003), and decreases the likelihood of getting consistent results for generating fertilizer recommendations.

References

Belcher, C.R., and J.L. Ragland. 1972. Phosphorus absorption by sod-planted corn (*Zea mays* L) from surface applied phosphorus. Agron. J. 64:754-756

Borges, R., and A.P. Mallarino. 2001. Deep banding phosphorus and potassium fertilizers for corn produced under ridge tillage. Soil Sci. Soc. Am. J. 65:376-384.

Cambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco, and A.E. Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58:1501-1511.

Carter, M.R., and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587-597.

Causarano, H.J., A.J. Franzluebbers, D.W. Reeves, and J.N. Shaw. 2006. Soil organic carbon sequestration in cotton production systems of the southeastern United States: a review. J. Environ. Qual. 35:1374-1383.

Coughenour, C.M., and S. Chamala. 2000. Reconstructing the farm landscape: The spread of conservation tillage in the United States. p. 255-295. *In*: Conservation tillage and cropping innovation: constructing the new culture of agriculture. Iowa State University Press, Ames, IA.

Cox, M.S., P.D. Gerard, M.C. Wardlaw, and M.J. Abshire. 2003. Variability of selected soil properties and their relationship with soybean yield. Soil Sci. Soc. Am. J. 67:1296-1302.

Edwards, J.H., C.W. Wood, D.L. Thurlow, and M.E. Ruf. 1992. Tillage and crop rotation effects on fertility status of a Hapludult soil. Soil Sci. Soc. Am. J. 56:1577-1582.

Frank, K., D. Beegle, and J.Denning. 1998. Phosphorus. p.21-29. 31-33. *In*: J.R. Brown (ed.) Recommended chemical soil test procedures for the north central region. North Central Regional Publication Number 221 (revised). Missouri Ag. Exp. Station SB 1001. Univ. of Missouri, Columbia, MO.

Holanda, F.S.R., D.B. Mengel, M.B. Paula, J.G. Carvaho, and J.C. Bertoni. 1998. Influence of crop rotations and tillage systems on phosphorus and potassium stratification and root distribution in the soil profile. Commun. Soil Sci. Plant Anal. 29:2383-2394.

Howard, D.D., M.E. Essington, and D.D. Tyler. 1999. Vertical phosphotus and potassium stratification in to-till cotton soils. Agron. J. 91:266-269.

Kitchen, N.R., J.L. Havlin, and D.G. Westfall. 1990. Soil sampling under no-till banded phosphorus. Soil Sci. Soc. Am. J. 54:1661-1665.

Leikam, D.F., R.E. Lamond, and D.B. Mengel. 2003. Soil test interpretations and fertilizer recommendations. Kansas state University Agricultural Experiment Station. Department of Agronomy. MF-2568.

Mackay, A.D., and S.A. Barber. 1985. Soil moisture effects on root growth and phosphorus uptake by corn. Agron. J. 77:519-523.

Mallarino, A.P. 1996. Patterns of spatial variability of phosphorus and potassium in no-tilled soils for two sampling scales. Soil Sci. Soc. Am. J. 60:1473-1481.

Mallarino, A.P., and R. Borges. 2006. Phosphorus and potassium distribution in soil following long-term band fertilization in different tillage systems. Soil Sci. Soc. Am. J. 70:702-707.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of the Mehlich 2 extractant. Comm. Soil Sci. Plant Anal. 15:1409-1416.

Moschler, W.W., and D.C. Martens. 1975. Nitrogen, phosphotus and potassium requirements in no-tillage and conventionally tilled corn. Soil Sci. Soc. Am. J. 39:886-891.

Nolin, M.C., G. Forand, R.R. Simard, A.N. Cambouris, and A. Karam. 2000. Soil specific relationships between corn/soybean yield, soil quality indicators and climatic data. *In*: P.C. Robert et al. (ed.) Proc. 5th Int. Conf. on Precision Agric., Bloomington, MN. 16-19 July 2000. ASA, CSSA, and SSSA, Madison, WI.

Olsen, S.R., F.S. Watanabe, and R.E. Danielson. 1961. Phosphorus absorption by corn roots as affected by moisture and phosphorus concentration. Soil Sci. Soc. Am. Proc. 25:289-294.

Robbins, S.G., and R.D. Voss. 1991. Phosphorus and potassium stratification in conservation tillage systems. J. Soil Water Conserv. 46:298-300.

Sainju, U.M., B.P. Singh, W.F. Whitehead. 2005. Tillage, cover crops, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. Agron. J. 97:1297-1290.

Sawchik, J. and A.P. Mallarino. 2008. Variability of soil properties, early phosphorus and potassium uptake, and incidence of pests and weeds in relation to soybean grain yield. Agron. J. 100:1450-1462.

Singh, T.A., G.W. Thomas, W.W. Moschler, and D.C. Martens. 1966. Phosphorus uptake by corn (*Zea mays* L.) under no-tillage and conventional practices. Agron. J. 58(2):147-148

Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agron. J. 59:240-243.

Tyler, D.D., and D.D. Howard. 1991. Soil sampling patterns for assessing no-tillage fertilization techniques. J. Fert. Issues 8:52-56.

Wollenhaupt, N.C., R.P. Wolkowski, and M.K. Clayton. 1994. Mapping soil test phosphorus and potassium for variable-rate fertilizer application. J. Prod. Agric. 7:441-448.

Wright, A.L., F.M. Hons, R.G. Lemon, M.L. McFarland, and R.L. Michols. 2007. Stratification of nutrients in soil for different tillage regimes and cotton rotations. Soil Tillage Res. 96:19-27.

CHAPTER 4 - Summary and Final Conclusions

Summary

Phosphorus stratification and the effects of stratification on crop productivity are not well understood in Kansas. This project came about because there are questions related to P stratification in arid environments that cannot currently be answered by researchers and industry personnel. The research conducted over the last three years indicated that P stratification may not decrease crop productivity in the environments represented by these sites. However, site specific considerations and experiment design need to be considered. The unfortunate situation in this study is that the two 'drier' sites also had high soil test P while the two sites with higher rainfall had lower soil test P. If one of the low rainfall sites had low soil test P, it would be easier to quantify P response under low rainfall conditions. Alternatively, it would also be interesting to see if a higher rainfall site would respond to P additions when the soil test P is above the critical level. This study was designed as a long-term study, so some of these questions may be answered with time. The low P application plots at Manhattan will likely draw the soil test P down to the point that P response may occur consistently in the next one or two crop rotations. Ottawa may build the soil test P level over time with the higher rates of P and high soil test P conditions may be observed with time.

The foresight by those that designed this as a long-term study was ingenious because with years of band and broadcast applications, the effects of P placement may change. Since humans and machines are not perfect, band application over time will result in a series of bands in one general area that will ultimately increase soil test P in a zone, not just a single band. So, if this dissertation was rewritten after year 10 of this study, it may stand to reason that crop response to deep band application may occur more frequently because the crops would be taking up P from an enriched zone, not one band. The soil testing portion may indicate that sampling from deep band applications is not as difficult as indicated here because sampling from the larger zone would require less precision than sampling from a small band.

Many producers are interested in long-term effects of P fertilizer placement because transferring to a deep placement management system may require equipment purchase and general management restructuring. Once a producer is committed to a new management system, convincing him/her to change is generally difficult. So, evaluating these systems in producer conditions and for lengthy periods of time is increasingly important.

There are, however, some negatives of long-term studies. The plot design is usually not changed and thus additional questions that may arise that are difficult to answer. Now that at least one rotation is complete, additional questions are easier to ask. One observation in Chapter 3 is that the P application rate at Scandia is not high enough to increase soil test P. It might be beneficial to add a higher P rate to evaluate the effects of P additions/removal in this high yielding site. So, how does one do this in a preexisting study? Two different recommendations come to mind. One is to increase the 17.4 kg P ha^{-1} rate to one that is higher than the 34.8 kg P ha^{-1} rate. This may be better than increasing the starter rate because the inflection point in the rate effect models shown in Chapter 2 occurred at rates slightly higher than the starter rate. Another option is to add plots to the study. The Scandia site has an alley between the replications, so the border plots could become application plots and a portion of the alley could become the border plots (refer to plot plan in Appendix A to view the layout). After intense sampling to define a starting point, the border plots could receive a P rate higher than the highest rate in this study. Phosphorus rates at other sites appear to be on target because they will both decrease soil test P significantly without P application and will increase soil test P at the high application rates.

The amount of data collected in the field is a concern from both a cost and labor perspective. To optimize the investment, taking appropriate samples to answer specific questions should be considered. All plant samples were important to understand effects of P at different points in the growing season. However, P uptake data could probably be improved by taking a larger sample for biomass yield calculation. The P concentration in the biomass appeared to be very accurate, which means subsampling and analytical work was excellent, but field variation and, possibly sample handling influenced biomass yield, and thus differences were not significant.

Another area to save time and money is in soil sampling. The concern for P stratification does not go deeper than 23 cm, so soil sampling below that depth is not necessary. Additionally, a better system to guide the sampling procedure would result in fewer plots that require re-sampling. One excellent idea from those involved in this study is to insert a string in the knife slot while P is applied so the exact P application location is known. Alternative methods may include taking samples as a slab oriented perpendicular to the crop row so a larger area of soil can be analyzed and the exact location of P can be determined.

When an applied study such as this is conducted, the usefulness to producers and extension personnel should be communicated. Producer interest in nutrient stratification is evident from personal communication with producers on several occasions. Some producers in Kansas actually sample fields by depth to try to understand the stratification present in their fields. Some have decided to apply P and K in a deep band to try to minimize stratification regardless of their understanding of the full effects of stratification. This study should relieve their concerns because placing P as a deep band did not increase yields, which means relieving P stratification does not impact yield. However, deep application of P does not decrease crop yield either. It was also demonstrated that when soil test P is low, P application is important to increase soil test P and improve crop yields.

Some agricultural areas near surface water bodies may be concerned about P stratification because of the high concentration near the soil surface and the dissolved reactive P migrating to surface water as discussed in Chapter 1. The knowledge that deep band P is available for plant uptake and that application deep in the soil does reduce stratification relative to broadcasting, means that deep band applied P may be a viable, environmentally friendly alternative to broadcast P application.

Final Thoughts

One important point to keep in mind is that as a society, we must be good stewards of our environment while maximizing food and feed production. The earth we live in is a system that everything we do will likely impact something we have not yet considered. While P application is only a small factor in global sustainability, it can have harmful effects if not managed properly. An example is that while broadcast application may be appropriate in one location, it may damage our ecosystem in another location. One day, our P supply will be depleted and the precious resource we have improperly managed will no longer be available. Our job is to do the best job at understanding these systems and educating the public to protect the world we live in and promote sustainable actions. It is exciting to be a part of agriculture at such a critical time, and to help educate our society.

Appendix A - Phosphorus Management in Reduced Tillage Systems Raw Data

This appendix contains all raw data collected that may be required to conduct additional analyses in the future. The data are arranged by site location and year with all plant data at the beginning and all soil data at the end of each site section. The plot plan for each location is displayed at the beginning of each section.

Scandia – North Central Kansas Experiment Field

P Management in Reduced Tillage (Scandia, KS)

Plot length = 55 ft, Alley = 20 ft

N

Trt.	Starter P	Broadcast P	Deep Band P	Total P	Broadcast P	Total P
	Corn				Soybeans	
1	0	0	0	0	0	0
2	20	0	0	20	0	0
3	0	40	0	40	0	0
4	20	20	0	40	0	0
5	0	0	40	40	0	0
6	20	0	20	40	0	0
7	0	80	0	80	0	0
8	20	60	0	80	0	0
9	0	0	80	80	0	0
10	20	0	60	80	0	0
11	20	60	0	80	40	40
12	20	0	60	80	40	40

B	401	402	403	404	405	406	407	408	409	410	411	412	B
	12	1	7	10	9	3	5	4	6	2	8	11	

Soybeans (even years) Corn (odd years)

B	413	414	415	416	417	418	419	420	421	422	423	424	B
	12	1	7	10	9	3	5	4	6	2	8	11	

Corn (even years) Soybeans (odd years)

B	301	302	303	304	305	306	307	308	309	310	311	312	B
	1	3	4	7	11	8	6	12	10	5	2	9	

Soybeans (even years) Corn (odd years)

B	313	314	315	316	317	318	319	320	321	322	323	324	B
	1	3	4	7	11	8	6	12	10	5	2	9	

Corn (even years) Soybeans (odd years)

B	201	202	203	204	205	206	207	208	209	210	211	212	B
	7	9	3	1	2	6	10	8	5	12	11	4	

Corn (even years) Soybeans (odd years)

B	213	214	215	216	217	218	219	220	221	222	223	224	B
	7	9	3	1	2	6	10	8	5	12	11	4	

Soybeans (even years) Corn (odd years)

B	101	102	103	104	105	106	107	108	109	110	111	112	B
	11	2	10	4	7	1	3	12	9	5	6	8	

Corn (even years) Soybeans (odd years)

B	113	114	115	116	117	118	119	120	121	122	123	124	B
	11	2	10	4	7	1	3	12	9	5	6	8	

Soybeans (even years) Corn (odd years)

Table A.1 Corn tissue nutrient analysis and biomass yield data from Scandia in the 2006 growing season.

Plot	--------------Ear Leaf-------------			---------------------Stover (black layer)---------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	(kg 15plnt^{-1})
101	2.63	0.21	2.57	0.76	0.05	1.59	1.26
102	2.82	0.21	2.50	0.92	0.06	1.78	1.01
103	2.82	0.22	2.62	0.70	0.05	1.95	0.80
104	2.89	0.22	2.84	0.73	0.05	1.79	0.91
105	2.64	0.23	2.95	0.82	0.06	1.88	0.91
106	2.63	0.19	2.52	0.70	0.05	1.74	1.33
107	2.77	0.23	2.79	0.92	0.06	1.96	1.22
108	3.19	0.28	3.07	0.85	0.06	1.69	1.01
109	2.91	0.23	2.92	0.69	0.05	1.66	0.93
110	2.73	0.21	2.70	0.62	0.04	1.31	0.75
111	2.62	0.21	2.80	0.76	0.05	1.78	0.92
112	2.87	0.23	2.78	0.63	0.04	1.35	1.00
201	2.65	0.20	2.54	0.61	0.05	1.63	0.91
202	2.72	0.21	2.57	0.66	0.04	1.48	0.69
203	2.59	0.20	2.78	0.63	0.04	1.93	0.68
204	2.57	0.18	2.63	0.53	0.03	1.64	0.80
205	2.69	0.20	2.66	0.68	0.05	2.06	0.89
206	2.60	0.21	2.69	0.70	0.04	2.03	0.78
207	2.47	0.20	2.60	0.61	0.04	1.78	0.83
208	2.67	0.22	2.70	0.66	0.04	2.11	0.68
209	2.71	0.20	2.57	0.61	0.04	1.71	0.97
210	2.57	0.20	2.61	0.69	0.04	2.48	0.82
211	2.80	0.23	2.72	0.56	0.05	1.53	0.83
212	2.51	0.19	2.53	0.83	0.05	1.67	0.95
313	2.68	0.19	2.65	0.85	0.04	2.40	1.02
314	2.91	0.26	3.17	0.81	0.05	2.18	0.89
315	2.94	0.25	3.03	0.65	0.04	1.56	0.98
316	2.76	0.24	2.95	0.82	0.06	1.84	1.06
317	2.67	0.21	2.60	0.60	0.04	1.87	0.83
318	2.83	0.23	2.65	0.78	0.04	2.21	0.88
319	2.81	0.23	2.99	0.75	0.04	2.08	0.98
320	2.46	0.21	2.66	0.71	0.04	1.88	1.17
321	2.86	0.24	2.92	0.73	0.05	1.94	1.07
322	2.99	0.25	3.02	0.73	0.05	2.09	1.02
323	2.81	0.23	2.90	0.76	0.05	2.15	0.95

324	2.85	0.24	2.98	0.85	0.05	1.74	0.88
413	2.68	0.23	2.77	0.74	0.06	1.58	0.93
414	2.97	0.22	2.68	0.77	0.04	1.49	1.06
415	2.86	0.24	2.64	0.79	0.05	2.55	0.95
416	2.83	0.23	2.69	0.63	0.04	1.99	1.06
417	2.71	0.22	2.67	0.82	0.05	2.45	0.91
418	2.79	0.21	2.45	0.80	0.05	2.31	0.92
419	2.56	0.20	2.72	0.83	0.06	2.15	1.12
420	2.90	0.23	2.45	0.69	0.05	2.15	1.03
421	2.92	0.23	2.53	1.04	0.09	2.40	1.13
422	2.95	0.24	2.75	0.67	0.05	1.88	1.03
423	2.62	0.23	2.73	0.81	0.06	2.17	1.08
424	3.14	0.25	2.44	0.61	0.05	1.31	1.11

Table A.2 Corn grain yield and nutrient analysis data from Scandia in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	-------------------------Grain-------------------------		
				N (%)	P (%)	K (%)
101	16.8	28.4	14.8	1.18	0.20	0.24
102	16.8	26.6	14.9	1.17	0.21	0.29
103	16.8	27.4	14.3	1.22	0.25	0.29
104	16.8	28.6	14.5	1.18	0.22	0.32
105	16.8	31.2	14.6	1.27	0.25	0.30
106	16.8	31.3	14.3	1.13	0.22	0.28
107	16.8	29.0	14.2	1.16	0.21	0.26
108	16.8	31.0	14.6	1.20	0.23	0.29
109	16.8	27.7	14.7	1.21	0.26	0.29
110	16.8	29.3	14.5	1.21	0.21	0.28
111	16.8	27.5	14.5	1.23	0.20	0.24
112	16.8	27.9	14.5	1.11	0.20	0.24
201	16.8	27.0	14.6	1.20	0.22	0.29
202	16.8	26.9	14.2	1.23	0.24	0.29
203	16.8	27.7	14.2	1.24	0.24	0.31
204	16.8	28.1	14.3	1.17	0.23	0.28
205	16.8	25.9	14.2	1.15	0.22	0.28
206	16.8	26.2	14.4	1.22	0.22	0.29
207	16.8	27.4	14.6	1.19	0.24	0.32
208	16.8	26.2	14.5	1.16	0.27	0.31
209	16.8	28.2	14.8	1.15	0.19	0.25
210	16.8	30.2	14.2	1.20	0.23	0.30
211	16.8	22.1	14.4	1.13	0.26	0.33
212	16.8	29.0	14.3	1.07	0.25	0.30
313	16.8	27.5	14.3	1.12	0.19	0.26
314	16.8	28.4	14.6	1.10	0.21	0.28
315	16.8	30.9	14.3	1.25	0.22	0.26
316	16.8	30.5	14.6	1.05	0.19	0.27
317	16.8	28.4	14.6	1.19	0.22	0.27
318	16.8	32.7	14.4	1.09	0.26	0.30
319	16.8	31.6	14.3	1.21	0.22	0.32
320	16.8	32.4	14.2	1.19	0.24	0.31
321	16.8	32.1	14.3	1.17	0.22	0.27
322	16.8	31.5	14.2	1.23	0.23	0.28
323	16.8	32.7	14.3	1.18	0.25	0.30

324	16.8	32.9	14.5	1.08	0.21	0.26
413	16.8	26.1	14.5	1.13	0.23	0.29
414	16.8	28.8	14.4	1.19	0.27	0.34
415	16.8	33.4	14.5	1.19	0.27	0.31
416	16.8	33.3	14.5	1.16	0.28	0.32
417	16.8	32.0	14.5	1.17	0.24	0.30
418	16.8	34.6	14.5	1.11	0.25	0.28
419	16.8	33.2	14.4	1.25	0.26	0.29
420	16.8	32.7	14.4	1.22	0.24	0.30
421	16.8	33.8	14.2	1.19	0.23	0.27
422	16.8	33.9	14.1	1.17	0.26	0.29
423	16.8	33.4	14.4	1.30	0.28	0.32
424	16.8	32.5	14.6	1.20	0.27	0.29

Table A.3 Soybean tissue nutrient analysis data from Scandia in the 2006 growing season.

Plot	---Trifoliates (R3)---		
	N	P	K
	(%)	(%)	(%)
113	4.64	0.30	2.56
114	5.46	0.33	2.27
115	4.73	0.29	2.50
116	4.99	0.34	2.24
117	5.19	0.28	2.19
118	4.49	0.26	2.61
119	5.28	0.31	2.23
120	4.97	0.39	2.52
121	5.81	0.31	2.42
122	5.01	0.29	2.26
123	5.08	0.32	2.32
124	5.18	0.34	2.10
213	5.18	0.31	2.48
214	5.14	0.29	2.30
215	5.11	0.27	2.25
216	5.04	0.28	2.40
217	4.32	0.26	2.68
218	5.26	0.28	2.25
219	5.25	0.29	2.14
220	5.48	0.35	2.29
221	5.12	0.27	2.24
222	5.15	0.34	2.47
223	5.05	0.33	2.21
224	4.84	0.34	2.75
301	5.17	0.27	2.16
302	5.56	0.37	2.27
303	5.10	0.31	2.57
304	5.58	0.38	2.28
305	5.58	0.38	2.26
306	5.14	0.29	2.24
307	5.42	0.38	2.36
308	5.24	0.30	2.20
309	4.94	0.32	2.36
310	4.98	0.29	2.22
311	5.03	0.28	2.31
312	5.05	0.29	2.35

401	5.27	0.39	2.37
402	4.68	0.32	2.53
403	5.17	0.34	2.44
404	5.25	0.35	2.57
405	5.20	0.34	2.33
406	5.72	0.34	2.35
407	5.30	0.33	2.36
408	5.49	0.37	2.25
409	5.43	0.33	2.32
410	5.40	0.33	2.25
411	5.30	0.34	2.30
412	4.77	0.34	2.61

Table A.4 Soybean grain yield and nutrient analysis data from Scandia in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	---------------------Grain---------------------		
				N (%)	P (%)	K (%)
113	16.8	7.6	11.1	6.01	0.48	1.81
114	16.8	8.2	11.2	5.01	0.39	1.72
115	16.8	7.9	11.2	5.71	0.48	1.83
116	16.8	8.8	11.2	5.85	0.45	1.74
117	16.8	7.8	11.1	5.48	0.47	1.80
118	16.8	7.5	11.0	6.09	0.46	1.85
119	16.8	7.7	11.0	5.95	0.46	1.78
120	16.8	8.6	11.2	5.92	0.54	1.85
121	16.8	7.4	11.2	5.50	0.46	1.73
122	16.8	7.4	11.1	5.63	0.45	1.78
123	16.8	8.2	11.2	5.85	0.52	1.82
124	16.8	8.6	11.0	5.95	0.51	1.82
213	16.8	8.5	11.3	5.36	0.41	1.78
214	16.8	7.5	11.1	5.77	0.48	1.79
215	16.8	8.4	11.0	5.47	0.41	1.71
216	16.8	7.7	11.1	5.70	0.48	1.73
217	16.8	8.2	11.0	6.09	0.44	1.81
218	16.8	7.8	11.1	6.38	0.49	1.88
219	16.8	8.1	11.0	5.88	0.45	1.79
220	16.8	8.8	11.1	5.82	0.46	1.74
221	16.8	8.3	11.1	5.67	0.42	1.69
222	16.8	8.6	11.3	6.08	0.52	1.79
223	16.8	8.8	11.3	5.80	0.49	1.79
224	16.8	9.1	11.0	5.82	0.54	1.83
301	16.8	7.3	11.1	5.83	0.48	1.81
302	16.8	8.8	11.2	5.85	0.47	1.84
303	16.8	7.8	11.2	5.73	0.45	1.77
304	16.8	8.5	11.1	5.86	0.53	1.82
305	16.8	8.2	11.2	6.15	0.51	1.85
306	16.8	8.3	11.1	6.01	0.47	1.79
307	16.8	8.3	11.0	6.12	0.52	1.79
308	16.8	9.1	11.1	5.94	0.50	1.81
309	16.8	8.7	11.0	6.24	0.49	1.81
310	16.8	8.1	11.2	6.03	0.48	1.82
311	16.8	7.5	11.0	5.69	0.44	1.79

312	16.8	8.2	11.0	5.92	0.50	1.83
401	16.8	7.2	11.0	5.86	0.47	1.93
402	16.8	6.7	11.2	5.88	0.51	1.97
403	16.8	7.0	11.0	6.11	0.45	1.91
404	16.8	7.7	11.0	5.18	0.40	1.66
405	16.8	6.9	11.0	5.43	0.41	1.78
406	16.8	7.9	11.1	6.32	0.56	1.98
407	16.8	8.8	11.0	6.27	0.52	1.97
408	16.8	8.4	11.2	5.73	0.51	1.92
409	16.8	8.4	11.0	6.07	0.49	1.91
410	16.8	7.8	11.1	5.90	0.45	1.80
411	16.8	9.9	11.1	5.75	0.49	1.88
412	16.8	8.8	11.1	6.29	0.56	1.95

Table A.5 Corn tissue nutrient analysis and biomass yield data from Scandia in the 2007 growing season.

Plot	------------------Ear Leaf------------------			--------------------------Stover (V5)--------------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	($kg\ 15plnt^{-1}$)
113	2.92	0.26	2.77	3.64	0.37	5.06	0.120
114	2.76	0.24	2.67	3.68	0.42	5.33	0.119
115	2.92	0.26	2.75	3.35	0.39	5.40	0.124
116	2.88	0.25	2.74	3.71	0.44	5.04	0.112
117	2.90	0.25	2.76	3.28	0.36	5.68	0.107
118	2.94	0.23	2.63	3.40	0.26	4.22	0.083
119	3.02	0.25	2.84	3.49	0.31	5.16	0.087
120	2.95	0.25	2.58	3.63	0.40	5.59	0.131
121	2.88	0.25	2.89	3.76	0.40	4.52	0.094
122	2.74	0.23	2.98	3.67	0.35	5.37	0.086
123	2.91	0.26	3.19	3.46	0.41	5.39	0.118
124	2.93	0.27	2.73	3.11	0.35	5.32	0.114
213	2.82	0.25	2.80	3.16	0.35	4.79	0.106
214	2.77	0.25	2.86	3.73	0.43	5.67	0.088
215	2.95	0.28	3.00	3.64	0.36	5.18	0.087
216	-	-	-	3.27	0.27	4.66	0.065
217	2.98	0.29	3.10	3.19	0.32	5.84	0.115
218	2.68	0.26	2.90	3.53	0.39	5.13	0.128
219	2.72	0.27	2.90	3.15	0.42	5.12	0.129
220	3.41	0.37	3.52	2.90	0.30	4.90	0.132
221	2.95	0.27	2.79	3.61	0.40	5.19	0.095
222	3.43	0.33	3.05	3.27	0.38	5.80	0.102
223	2.79	0.28	2.89	3.36	0.38	5.48	0.106
224	2.75	0.27	2.86	3.64	0.36	5.22	0.077
301	2.57	0.21	2.61	3.73	0.32	4.47	0.060
302	3.23	0.32	3.34	3.69	0.35	4.35	0.066
303	2.63	0.25	2.99	3.71	0.41	4.77	0.112
304	2.79	0.28	2.99	3.38	0.40	5.29	0.100
305	2.81	0.27	2.74	3.30	0.37	4.26	0.106
306	2.95	0.29	2.86	3.45	0.38	4.81	0.116
307	2.94	0.28	2.97	3.04	0.34	5.50	0.098
308	2.31	0.21	2.79	3.65	0.35	4.78	0.069
309	3.09	0.29	2.98	3.44	0.38	5.08	0.106
310	2.89	0.25	2.67	3.54	0.34	4.65	0.093
311	3.10	0.28	2.87	3.35	0.33	5.15	0.087

312	3.10	0.28	2.95	3.60	0.41	4.89	0.080
401	2.81	0.27	2.78	3.17	0.35	5.34	0.095
402	2.65	0.22	2.62	3.24	0.29	4.97	0.052
403	3.12	0.30	3.02	3.51	0.46	5.30	0.095
404	3.64	0.37	3.57	3.43	0.48	5.91	0.123
405	2.80	0.24	2.65	3.62	0.36	4.80	0.110
406	2.82	0.27	2.90	3.39	0.39	4.84	0.103
407	2.74	0.28	3.14	3.22	0.38	5.34	0.101
408	2.70	0.29	2.84	3.13	0.37	4.85	0.091
409	2.68	0.28	3.13	3.71	0.37	4.80	0.097
410	3.10	0.28	2.95	3.62	0.39	4.68	0.112
411	2.67	0.26	2.75	3.13	0.44	5.56	0.098
412	2.50	0.23	2.82	3.34	0.36	5.11	0.092

Table A.5 Continued.

Plot	---Stover (Black Layer)---			
	N (%)	P (%)	K (%)	Dry Weight (kg 15plnt^{-1})
113	0.71	0.07	1.06	1.50
114	0.54	0.05	1.14	1.55
115	0.67	0.07	1.87	1.48
116	0.70	0.07	1.58	1.49
117	0.73	0.06	1.61	1.43
118	0.58	0.04	1.86	1.38
119	0.85	0.07	1.70	1.52
120	0.73	0.06	1.41	1.50
121	0.59	0.04	1.48	1.50
122	0.42	0.03	1.60	1.20
123	0.57	0.05	1.57	1.33
124	0.52	0.05	1.93	1.44
213	0.56	0.05	1.26	1.18
214	0.70	0.06	1.62	1.48
215	0.87	0.07	1.81	1.39
216	0.71	0.05	1.70	1.22
217	0.74	0.05	1.48	1.21
218	0.83	0.07	2.18	1.43
219	0.83	0.09	1.81	1.42
220	0.88	0.08	1.97	1.24
221	0.97	0.07	2.65	1.06
222	0.67	0.07	1.77	1.04
223	0.79	0.07	1.63	1.70
224	0.76	0.07	2.17	1.36
301	0.73	0.08	2.23	1.30
302	0.79	0.09	1.73	1.37
303	0.69	0.08	1.52	1.41
304	0.74	0.08	1.92	1.10
305	0.64	0.06	1.70	1.54
306	0.74	0.07	2.55	0.84
307	0.75	0.19	1.49	1.20
308	0.72	0.07	1.83	1.33
309	0.67	0.06	1.80	1.16
310	0.80	0.06	2.20	1.12
311	0.62	0.07	2.00	1.08
312	0.65	0.05	1.74	1.33

401	0.39	0.06	1.21	1.19
402	0.46	0.04	1.67	1.38
403	0.50	0.04	1.30	1.03
404	0.62	0.06	2.06	1.08
405	0.47	0.04	1.07	1.89
406	0.57	0.04	1.79	0.90
407	0.82	0.09	1.54	0.99
408	0.66	0.06	1.79	1.22
409	0.84	0.07	2.60	1.16
410	0.66	0.05	2.03	1.01
411	0.51	0.06	1.60	1.07
412	0.62	0.06	1.90	1.05

Table A.6 Corn grain yield and nutrient analysis data from Scandia in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	----------Grain----------		
			N (%)	P (%)	K (%)
113	16.8	36.6	1.15	0.23	0.31
114	16.8	32.4	1.05	0.27	0.35
115	16.8	36.9	1.16	0.25	0.32
116	16.8	37.5	1.06	0.25	0.35
117	16.8	37.1	1.13	0.26	0.36
118	16.8	29.5	1.10	0.24	0.33
119	16.8	36.8	1.19	0.28	0.34
120	16.8	36.3	1.09	0.29	0.37
121	16.8	37.7	1.19	0.25	0.33
122	16.8	37.1	1.13	0.22	0.32
123	16.8	37.0	1.19	0.24	0.34
124	16.8	39.1	1.14	0.25	0.34
213	16.8	32.9	1.20	0.26	0.34
214	16.8	36.2	1.13	0.27	0.36
215	16.8	33.9	1.08	0.26	0.33
216	16.8	29.2	1.20	0.29	0.37
217	16.8	34.7	1.16	0.23	0.34
218	16.8	34.7	1.17	0.26	0.35
219	16.8	34.6	1.16	0.23	0.34
220	16.8	35.1	1.05	0.28	0.36
221	16.8	36.0	1.09	0.26	0.33
222	16.8	36.2	1.13	0.23	0.32
223	16.8	36.1	1.10	0.28	0.35
224	16.8	36.1	1.04	0.25	0.33
301	16.8	27.2	1.11	0.24	0.30
302	16.8	36.2	1.14	0.20	0.29
303	16.8	38.2	1.15	0.22	0.34
304	16.8	38.3	1.15	0.25	0.34
305	16.8	37.6	1.17	0.22	0.32
306	16.8	36.2	1.15	0.21	0.29
307	16.8	37.7	1.03	0.21	0.31
308	16.8	37.6	1.09	0.25	0.33
309	16.8	36.8	1.09	0.23	0.31
310	16.8	37.8	1.11	0.18	0.28
311	16.8	37.8	1.20	0.26	0.35

312	16.8	37.2	1.05	0.27	0.34
401	16.8	39.2	1.13	0.24	0.31
402	16.8	30.0	1.18	0.25	0.33
403	16.8	38.8	1.21	0.25	0.33
404	16.8	38.8	1.13	0.21	0.32
405	16.8	36.7	1.20	0.24	0.30
406	16.8	36.6	1.12	0.18	0.31
407	16.8	37.9	1.17	0.22	0.32
408	16.8	36.3	1.15	0.27	0.35
409	16.8	36.5	1.15	0.23	0.32
410	16.8	37.0	1.27	0.27	0.34
411	16.8	38.2	1.18	0.25	0.35
412	16.8	37.1	1.25	0.29	0.35

Table A.7 Soybean tissue nutrient analysis and biomass yield data from Scandia in the 2007 growing season.

Plot	--------------------Trifoliates (V4)----------------------			---------------------Trifoliates (R3)---------------------		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
101	5.02	0.29	2.44	4.71	0.28	1.61
102	5.19	0.29	2.48	4.67	0.27	1.69
103	5.40	0.33	2.59	4.69	0.28	1.91
104	5.24	0.31	2.60	4.67	0.26	1.69
105	5.30	0.34	2.77	4.46	0.23	1.86
106	5.43	0.32	2.59	4.74	0.25	1.78
107	5.21	0.32	2.76	4.76	0.26	1.67
108	5.33	0.34	2.54	4.99	0.28	1.66
109	5.09	0.31	2.54	3.85	0.18	1.26
110	5.27	0.31	2.57	4.77	0.24	1.62
111	5.22	0.31	2.60	4.81	0.22	1.66
112	5.42	0.32	2.69	4.89	0.24	1.63
201	5.39	0.31	2.53	4.37	0.25	1.66
202	5.27	0.30	2.77	4.64	0.26	1.67
203	5.40	0.31	2.53	4.17	0.23	1.68
204	5.56	0.30	2.53	4.20	0.22	1.72
205	5.45	0.31	2.66	4.44	0.22	1.73
206	5.29	0.30	2.53	4.40	0.22	1.70
207	5.24	0.32	2.76	4.57	0.24	1.65
208	5.39	0.32	2.64	4.43	0.25	1.70
209	5.19	0.31	2.46	4.58	0.23	1.69
210	5.03	0.32	2.64	4.54	0.24	1.72
211	5.02	0.32	2.63	4.68	0.26	1.75
212	5.39	0.30	2.58	4.82	0.26	1.65
313	5.07	0.29	2.76	4.84	0.25	1.71
314	5.34	0.33	2.69	4.56	0.24	1.74
315	5.24	0.32	2.62	4.57	0.23	1.81
316	4.89	0.33	2.72	4.92	0.24	1.73
317	5.17	0.33	2.56	4.90	0.27	1.67
318	4.87	0.31	2.51	4.75	0.24	1.64
319	5.02	0.32	2.62	4.87	0.26	1.66
320	5.17	0.35	2.54	4.85	0.24	1.62
321	4.92	0.32	2.43	4.69	0.25	1.66
322	4.96	0.31	2.66	4.86	0.24	1.66
323	5.02	0.34	2.56	4.75	0.26	1.71
324	5.12	0.34	2.64	4.89	0.25	1.71

413	5.27	0.34	2.65	4.88	0.26	1.58
414	5.37	0.32	2.66	4.96	0.23	1.69
415	5.24	0.33	2.56	4.85	0.25	1.61
416	5.28	0.34	2.70	5.07	0.27	1.60
417	5.28	0.33	2.51	4.76	0.24	1.67
418	5.29	0.34	2.52	4.73	0.27	1.70
419	5.20	0.31	2.51	4.76	0.24	1.69
420	5.46	0.32	2.66	4.78	0.27	1.62
421	5.13	0.30	2.39	4.90	0.24	1.72
422	5.19	0.32	2.41	4.90	0.26	1.58
423	5.39	0.33	2.55	4.83	0.25	1.65
424	5.32	0.33	2.61	4.76	0.28	1.63

Table A.7 Continued.

Plot	N (%)	P (%)	K (%)	Dry Weight (kg 15plnt^{-1})
	---Stover (Black Layer)---			
101	2.35	0.25	2.08	1.50
102	1.30	0.13	2.62	1.55
103	1.15	0.12	1.86	1.48
104	1.69	0.16	2.35	1.49
105	0.89	0.13	1.98	1.43
106	1.46	0.17	2.57	1.38
107	1.69	0.18	2.29	1.52
108	2.67	0.27	2.53	1.50
109	2.61	0.22	2.40	1.50
110	2.15	0.19	2.15	1.20
111	0.81	0.08	1.83	1.33
112	2.54	0.25	2.30	1.44
201	0.77	0.10	1.98	1.82
202	1.06	0.10	2.14	1.48
203	0.98	0.08	2.56	1.39
204	1.05	0.08	2.09	1.22
205	1.67	0.15	2.48	1.21
206	1.74	0.17	2.33	1.43
207	1.04	0.09	2.38	1.42
208	2.65	0.24	2.20	1.24
209	1.26	0.11	1.95	1.06
210	1.26	0.14	2.08	1.04
211	1.25	0.14	1.82	1.70
212	1.54	0.15	2.39	1.36
313	1.08	0.12	2.16	1.30
314	0.80	0.11	2.29	1.37
315	2.00	0.17	2.28	1.41
316	0.72	0.09	2.03	1.10
317	0.62	0.08	1.94	1.54
318	0.55	0.06	1.82	0.84
319	2.55	0.22	2.24	1.20
320	0.97	0.13	2.45	1.33
321	1.11	0.15	2.47	1.16
322	0.69	0.08	2.09	1.12
323	2.52	0.27	2.43	1.08
324	0.76	0.13	2.16	1.33

413	1.11	0.13	2.39	1.19
414	1.52	0.12	2.22	1.38
415	1.21	0.12	2.11	1.03
416	1.29	0.12	2.38	1.08
417	2.08	0.21	2.47	1.89
418	1.75	0.18	2.48	0.90
419	1.71	0.18	2.14	0.99
420	1.30	0.16	2.45	1.22
421	0.93	0.12	2.25	1.16
422	1.71	0.17	2.26	1.01
423	1.83	0.20	2.09	1.07
424	0.76	0.13	2.08	1.05

Table A.8 Soybean grain yield and nutrient analysis data from Scandia in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Grain N (%)	Grain P (%)	Grain K (%)
101	16.8	11.0	5.86	0.49	1.90
102	16.8	10.5	5.97	0.47	1.88
103	16.8	10.1	5.81	0.47	1.80
104	16.8	10.9	5.68	0.46	1.81
105	16.8	11.2	5.90	0.50	1.87
106	16.8	9.0	5.83	0.48	1.84
107	16.8	10.7	5.71	0.48	1.76
108	16.8	11.9	5.85	0.49	1.86
109	16.8	10.7	5.70	0.48	1.83
110	16.8	10.1	5.89	0.44	1.77
111	16.8	10.1	5.92	0.44	1.79
112	16.8	10.9	6.08	0.45	1.85
201	16.8	10.5	5.86	0.47	1.86
202	16.8	10.5	5.99	0.47	1.87
203	16.8	10.5	6.00	0.48	1.87
204	16.8	9.1	5.71	0.47	1.87
205	16.8	10.3	5.81	0.48	1.82
206	16.8	10.3	5.95	0.52	1.86
207	16.8	10.5	5.98	0.50	1.84
208	16.8	10.9	5.97	0.57	1.90
209	16.8	10.2	5.85	0.43	1.86
210	16.8	11.4	5.87	0.47	1.84
211	16.8	10.9	5.95	0.46	1.81
212	16.8	10.8	5.82	0.47	1.85
313	16.8	9.0	6.00	0.47	1.78
314	16.8	10.7	5.94	0.47	1.87
315	16.8	10.5	5.80	0.45	1.82
316	16.8	10.7	5.84	0.53	1.83
317	16.8	11.2	5.88	0.48	1.78
318	16.8	11.7	5.84	0.48	1.81
319	16.8	10.7	6.03	0.47	1.85
320	16.8	12.8	5.96	0.50	1.85
321	16.8	10.6	5.85	0.54	1.84
322	16.8	10.7	6.06	0.49	1.89
323	16.8	10.7	5.85	0.52	1.79

324	16.8	10.9	5.69	0.56	1.83
413	16.8	12.1	5.95	0.49	1.85
414	16.8	9.1	6.05	0.51	1.80
415	16.8	10.6	5.96	0.54	1.87
416	16.8	10.4	5.97	0.50	1.85
417	16.8	10.5	5.95	0.48	1.83
418	16.8	10.7	7.05	0.48	1.86
419	16.8	10.8	6.06	0.47	1.82
420	16.8	11.0	6.01	0.49	1.80
421	16.8	10.6	5.77	0.48	1.80
422	16.8	10.7	6.00	0.51	1.88
423	16.8	11.8	6.05	0.54	1.86
424	16.8	11.7	5.83	0.54	1.85

Table A.9 Corn tissue nutrient analysis and biomass yield data from Scandia in the 2008 growing season.

Plot	Ear Leaf	----------------------Stover (V5)-----------------------	
	P	P	Dry Weight
	(%)	(%)	(kg $15plnt^{-1}$)
101	0.256	0.393	0.238
102	0.238	0.359	0.223
103	0.252	0.386	0.290
104	0.261	0.331	0.207
105	0.272	0.378	0.285
106	0.231	0.335	0.185
107	0.240	0.389	0.195
108	0.248	0.430	0.241
109	0.229	0.355	0.178
110	0.253	0.395	0.205
111	0.244	0.412	0.184
112	0.277	0.367	0.212
201	0.275	0.430	0.236
202	0.231	0.349	0.196
203	0.283	0.343	0.177
204	0.158	0.322	0.203
205	0.249	0.339	0.190
206	0.283	0.353	0.230
207	0.272	0.430	0.194
208	0.291	0.416	0.198
209	0.292	0.416	0.241
210	0.283	0.479	0.223
211	0.276	0.425	0.196
212	0.248	0.355	0.184
313	0.245	0.301	0.180
314	0.207	0.352	0.193
315	0.273	0.344	0.224
316	0.296	0.425	0.294
317	0.280	0.398	0.242
318	0.279	0.368	0.196
319	0.276	0.376	0.258
320	0.292	0.488	0.216
321	0.251	0.392	0.258
322	0.268	0.387	0.215
323	0.257	0.335	0.213

324	0.217	0.320	0.188
413	0.271	0.444	0.261
414	0.242	0.358	0.176
415	0.275	0.407	0.241
416	0.264	0.384	0.292
417	0.256	0.316	0.213
418	0.264	0.408	0.195
419	0.249	0.354	0.289
420	0.261	0.328	0.207
421	0.259	0.304	0.278
422	0.255	0.327	0.233
423	0.279	0.401	0.214
424	0.265	0.360	0.238

Table A.10 Corn grain yield and nutrient analysis data from Scandia in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Grain P (%)
101	16.8	34.8	16.7	0.311
102	16.8	34.9	16.5	0.241
103	16.8	38.8	16.2	0.267
104	16.8	38.1	16.2	0.240
105	16.8	36.2	16.3	0.293
106	16.8	33.2	16.2	0.226
107	16.8	36.3	16.1	0.255
108	16.8	38.1	16.1	0.289
109	16.8	37.3	16.2	0.309
110	16.8	36.7	16.2	0.284
111	16.8	37.8	16.3	0.274
112	16.8	35.4	16.2	0.228
201	16.8	34.5	16.2	0.286
202	16.8	36.7	16.2	0.281
203	16.8	36.2	16.3	0.260
204	16.8	30.8	16.0	0.221
205	16.8	37.2	16.2	0.230
206	16.8	38.3	16.1	0.288
207	16.8	38.2	16.2	0.297
208	16.8	37.9	16.1	0.323
209	16.8	36.1	16.2	0.232
210	16.8	36.7	16.3	0.292
211	16.8	37.9	16.1	0.253
212	16.8	37.8	16.1	0.281
313	16.8	29.5	16.2	0.250
314	16.8	32.9	16.1	0.238
315	16.8	37.9	16.1	0.246
316	16.8	34.9	16.0	0.296
317	16.8	38.0	16.0	0.257
318	16.8	37.9	16.2	0.303
319	16.8	35.9	16.1	0.267
320	16.8	37.9	16.1	0.289
321	16.8	38.1	16.1	0.274
322	16.8	35.7	16.2	0.285
323	16.8	38.1	16.0	0.260
324	16.8	36.3	16.0	0.275

413	16.8	36.2	16.1	0.273
414	16.8	30.1	16.2	0.271
415	16.8	34.8	16.1	0.305
416	16.8	38.1	16.2	0.309
417	16.8	37.2	16.2	0.258
418	16.8	36.9	16.2	0.279
419	16.8	36.1	16.1	0.282
420	16.8	38.8	16.2	0.256
421	16.8	38.1	16.1	0.281
422	16.8	38.0	16.2	0.310
423	16.8	37.3	16.2	0.241
424	16.8	37.8	16.0	0.323

Table A.11 Soybean tissue nutrient analysis and biomass yield data from Scandia in the 2008 growing season.

Plot	-------------------------------Stover (V4)--------------------------------		Trifoliates (R3)
	P (%)	Dry Weight (kg 15plnt^{-1})	P (%)
113	0.312	0.089	0.33
114	0.291	0.099	0.32
115	0.298	0.089	0.33
116	0.304	0.085	0.37
117	0.287	0.115	0.31
118	0.278	0.091	0.32
119	0.283	0.096	0.33
120	0.314	0.107	0.35
121	0.292	0.099	0.32
122	0.268	0.092	0.29
123	0.330	0.085	0.31
124	-	0.088	0.30
213	0.301	0.122	0.34
214	0.300	0.114	0.32
215	0.289	0.091	0.31
216	0.268	0.106	0.30
217	0.309	0.112	0.32
218	0.323	0.103	0.32
219	0.316	0.107	0.34
220	0.329	0.101	0.35
221	0.261	0.113	0.37
222	0.295	0.091	0.31
223	0.313	0.102	0.37
224	0.320	0.116	0.35
301	0.293	0.100	0.32
302	0.303	0.120	0.30
303	0.295	0.114	0.33
304	0.324	0.089	0.33
305	0.308	0.107	0.36
306	0.290	0.105	0.32
307	0.323	0.106	0.31
308	0.316	0.114	0.34
309	0.348	0.115	0.32
310	0.308	0.110	0.31
311	0.281	0.105	0.31

312	0.320	0.097	0.32
401	0.301	0.096	0.32
402	0.289	0.126	0.31
403	0.303	0.126	0.31
404	0.331	0.121	0.33
405	0.305	0.115	0.31
406	0.306	0.121	0.32
407	0.310	0.130	0.34
408	0.321	0.112	0.32
409	0.311	0.124	0.30
410	0.299	0.137	0.33
411	0.337	0.104	0.33
412	0.330	0.102	0.33

Table A.12 Soybean grain yield and nutrient analysis data from Scandia in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
113	16.8	10.7	12.1	25.6	0.499
114	16.8	10.1	12.0	25.6	0.342
115	16.8	10.1	12.0	25.2	0.449
116	16.8	9.9	11.8	25.9	0.409
117	16.8	10.9	11.9	24.5	0.459
118	16.8	10.1	12.0	25.7	0.392
119	16.8	10.1	12.0	25.2	0.428
120	16.8	10.9	12.1	25.9	0.491
121	16.8	10.5	12.0	25.2	0.401
122	16.8	10.2	11.9	25.2	0.432
123	16.8	10.0	12.0	24.2	0.453
124	16.8	9.5	12.1	25.2	0.475
213	16.8	10.1	12.0	25.9	0.446
214	16.8	10.9	12.0	25.8	0.465
215	16.8	10.8	12.0	25.7	0.431
216	16.8	11.1	11.9	25.2	0.419
217	16.8	10.2	11.9	25.7	0.412
218	16.8	10.7	12.0	25.9	0.444
219	16.8	10.7	12.0	25.7	0.422
220	16.8	9.9	11.8	25.4	0.438
221	16.8	10.8	12.0	24.7	0.386
222	16.8	11.2	12.1	25.7	0.506
223	16.8	9.9	12.0	24.8	0.484
224	16.8	11.2	12.0	25.7	0.518
301	16.8	9.9	12.0	24.1	0.403
302	16.8	10.1	12.1	25.8	0.394
303	16.8	9.1	12.0	24.8	0.376
304	16.8	11.2	12.0	25.4	0.433
305	16.8	11.2	12.0	25.0	0.424
306	16.8	10.2	11.5	25.6	0.445
307	16.8	10.9	11.9	25.6	0.441
308	16.8	11.7	11.9	25.1	0.488
309	16.8	11.4	12.0	24.9	0.463
310	16.8	11.1	12.0	25.6	0.459
311	16.8	10.5	12.0	24.8	0.445
312	16.8	11.3	11.8	25.9	0.508

401	16.8	11.4	11.9	25.7	0.479
402	16.8	10.4	12.1	26.0	0.485
403	16.8	10.8	12.0	25.7	0.428
404	16.8	11.1	12.0	25.7	0.570
405	16.8	11.0	11.9	25.3	0.467
406	16.8	11.6	12.0	26.0	0.498
407	16.8	11.2	12.0	25.5	0.471
408	16.8	10.2	11.9	25.7	0.496
409	16.8	10.2	11.9	25.5	0.484
410	16.8	10.5	12.0	25.3	0.454
411	16.8	10.8	12.0	25.7	0.500
412	16.8	11.0	12.1	25.6	0.509

Table A.13 Initial soil sample data from Scandia.

Plots	Depth (m)	pH	Buffer pH	P (ppm)	K (ppm)	SO_4^{2+} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	OM (%)	Cl^- (ppm)
101-112	0-0.08	6.4	6.6	10	573	6.4	6.4	11.5	2.9	10.2
101-112	0.08-0.15	5.8	6.6	4	464	8.0	7.4	6.8	2.3	8.0
101-112	0.15-0.23	5.8	6.4	3	416	11.3	5.8	4.4	2.0	9.8
101-112	0.23-0.31	6.4	6.8	6	393	11.1	5.5	3.1	1.7	9.7
101-112	0.31-0.61	6.9	-	6	373	11.6	4.4	1.7	1.1	8.1
101-112	0.61-0.91	7.5	-	14	343	13.0	4.4	1.4	0.7	14.1
113-124	0-0.08	6.8	-	5	577	7.4	4.7	7.7	2.7	8.7
113-124	0.08-0.15	6.3	6.4	5	451	8.1	6.3	6.0	2.5	7.0
113-124	0.15-0.23	5.9	6.5	3	398	11.0	6.4	4.1	1.8	8.0
114-127	0.23-0.31	6.3	6.9	2	393	10.2	5.5	2.8	1.7	7.7
113-124	0.31-0.61	6.9	-	5	371	9.3	5.9	2.0	1.1	7.1
113-124	0.61-0.91	7.6	-	17	356	13.7	4.5	1.3	0.8	12.2
201-212	0-0.08	6.7	-	18	580	5.9	3.3	5.9	2.6	8.4
201-212	0.08-0.15	6.2	6.6	7	422	8.3	4.3	5.8	2.1	8.0
201-212	0.15-0.23	6.0	6.5	9	362	10.1	4.2	4.1	2.2	8.6
201-212	0.23-0.31	6.4	6.9	9	398	9.8	6.7	3.1	2.0	8.9
201-212	0.31-0.61	6.8	-	6	383	11.4	4.8	1.5	1.1	9.4
201-212	0.61-0.91	7.3	-	33	366	19.3	5.5	1.3	0.7	22.6
213-224	0-0.08	6.9	-	9	563	3.9	4.0	7.9	3.0	9.2
213-224	0.08-0.15	5.9	6.5	9	482	2.9	4.3	6.4	2.1	7.1
213-224	0.15-0.23	5.6	6.5	8	409	2.4	5.8	4.2	1.9	8.4
213-224	0.23-0.31	5.9	6.5	9	383	0.2	6.2	3.2	1.8	8.2
213-224	0.31-0.61	6.8	-	4	359	12.7	5.1	1.8	1.1	7.4
213-224	0.61-0.91	7.4	-	16	342	16.5	6.3	1.2	0.7	14.3
301-312	0-0.08	6.9	-	9	599	8.5	4.2	8.8	2.9	8.1
301-312	0.08-0.15	6.6	-	4	441	9.9	5.9	5.4	2.4	9.9
301-312	0.15-0.23	6.2	6.7	4	385	12.0	5.7	3.2	2.1	10.0
301-312	0.23-0.31	6.5	-	3	368	11.7	5.0	2.9	2.0	10.3
301-312	0.31-0.61	7.0	-	4	398	15.6	6.5	1.8	1.2	9.9
301-312	0.61-0.91	7.0	-	21	352	25.1	5.0	1.1	0.7	18.3
313-324	0-0.08	7.3	-	7	606	9.6	5.5	11.3	3.1	8.5
313-324	0.08-0.15	6.7	-	5	455	11.5	8.2	7.1	2.2	8.1
313-324	0.15-0.23	5.9	6.6	5	400	16.7	4.7	4.9	2.3	9.8
313-324	0.23-0.31	6.3	6.7	4	396	16.8	5.3	3.1	1.8	10.2

313-324	0.31-0.61	6.8	-	4	380	16.2	5.2	1.8	1.3	7.4
313-324	0.61-0.91	6.9	-	22	358	20.4	6.0	1.3	0.8	11.8
401-412	0-0.08	7.5	-	8	589	12.6	10.9	8.2	2.8	9.2
401-412	0.08-0.15	6.7	-	6	452	11.9	5.2	6.1	2.3	9.0
401-412	0.15-0.23	6.5	-	4	377	15.9	4.6	5.2	2.2	10.8
401-412	0.23-0.31	6.3	6.8	3	391	16.2	7.5	3.5	1.8	10.7
401-412	0.31-0.61	6.6	-	4	398	19.5	6.5	2.4	1.4	8.6
401-412	0.61-0.91	7.0	-	16	391	30.7	6.3	1.5	0.7	13.8
413-424	0-0.08	7.4	-	10	603	12.8	6.1	11.3	2.9	8.6
413-424	0.08-0.15	7.0	-	5	447	14.4	4.4	4.5	2.2	7.7
413-424	0.15-0.23	6.1	6.6	4	364	11.3	7.0	5.6	2.3	9.2
413-424	0.23-0.31	6.3	6.9	7	346	10.9	6.5	4.0	2	8.7
413-424	0.31-0.61	6.9	-	3	362	10.3	5.9	2.1	1.4	6.94
413-424	0.61-0.91	7.2	-	32	344	15.6	6.5	1.1	0.9	17.16

Table A.14 Soil sample data from Scandia collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

Plot	Depth (m)	Location	P (ppm)
115	0-0.08	Row	14
115	0.08-0.15	Row	37
115	0.15-0.23	Row	11
115	0.23-0.31	Row	4
115	0.31-0.61	Row	5
115	0-0.08	Row Middle	11
115	0.08-0.15	Row Middle	5
115	0.15-0.23	Row Middle	4
115	0.23-0.31	Row Middle	3
115	0.31-0.61	Row Middle	6
118	0-0.08	Row	7
118	0.08-0.15	Row	5
118	0.15-0.23	Row	4
118	0.23-0.31	Row	3
118	0.31-0.61	Row	5
118	0-0.08	Row Middle	7
118	0.08-0.15	Row Middle	6
118	0.15-0.23	Row Middle	4
118	0.23-0.31	Row Middle	3
118	0.31-0.61	Row Middle	5
120	0-0.08	Row	50
120	0.08-0.15	Row	7
120	0.15-0.23	Row	4
120	0.23-0.31	Row	3
120	0.31-0.61	Row	4
120	0-0.08	Row Middle	13
120	0.08-0.15	Row Middle	6
120	0.15-0.23	Row Middle	4
120	0.23-0.31	Row Middle	3
120	0.31-0.61	Row Middle	10
121	0-0.08	Row	8
121	0.08-0.15	Row	6
121	0.15-0.23	Row	4
121	0.23-0.31	Row	3

121	0.31-0.61	Row	3
121	0-0.08	Row Middle	6
121	0.08-0.15	Row Middle	6
121	0.15-0.23	Row Middle	4
121	0.23-0.31	Row Middle	3
121	0.31-0.61	Row Middle	5
124	0-0.08	Row	34
124	0.08-0.15	Row	8
124	0.15-0.23	Row	5
124	0.23-0.31	Row	4
124	0.31-0.61	Row	6
124	0-0.08	Row Middle	15
124	0.08-0.15	Row Middle	6
124	0.15-0.23	Row Middle	5
124	0.23-0.31	Row Middle	3
124	0.31-0.61	Row Middle	4
214	0-0.08	Row	9
214	0.08-0.15	Row	41
214	0.15-0.23	Row	17
214	0.23-0.31	Row	3
214	0.31-0.61	Row	4
214	0-0.08	Row Middle	7
214	0.08-0.15	Row Middle	6
214	0.15-0.23	Row Middle	3
214	0.23-0.31	Row Middle	2
214	0.31-0.61	Row Middle	13
216	0-0.08	Row	8
216	0.08-0.15	Row	6
216	0.15-0.23	Row	5
216	0.23-0.31	Row	3
216	0.31-0.61	Row	4
216	0-0.08	Row Middle	8
216	0.08-0.15	Row Middle	6
216	0.15-0.23	Row Middle	4
216	0.23-0.31	Row Middle	3
216	0.31-0.61	Row Middle	4
219	0-0.08	Row	17

219	0.08-0.15	Row	10
219	0.15-0.23	Row	8
219	0.23-0.31	Row	5
219	0.31-0.61	Row	4
219	0-0.08	Row Middle	10
219	0.08-0.15	Row Middle	6
219	0.15-0.23	Row Middle	6
219	0.23-0.31	Row Middle	3
219	0.31-0.61	Row Middle	3
220	0-0.08	Row	56
220	0.08-0.15	Row	20
220	0.15-0.23	Row	6
220	0.23-0.31	Row	4
220	0.31-0.61	Row	4
220	0-0.08	Row Middle	16
220	0.08-0.15	Row Middle	8
220	0.15-0.23	Row Middle	8
220	0.23-0.31	Row Middle	4
220	0.31-0.61	Row Middle	5
222	0-0.08	Row	23
222	0.08-0.15	Row	7
222	0.15-0.23	Row	5
222	0.23-0.31	Row	3
222	0.31-0.61	Row	3
222	0-0.08	Row Middle	9
222	0.08-0.15	Row Middle	5
222	0.15-0.23	Row Middle	4
222	0.23-0.31	Row Middle	3
222	0.31-0.61	Row Middle	5
301	0-0.08	Row	23
301	0.08-0.15	Row	8
301	0.15-0.23	Row	7
301	0.23-0.31	Row	6
301	0.31-0.61	Row	5
301	0-0.08	Row Middle	11
301	0.08-0.15	Row Middle	7
301	0.15-0.23	Row Middle	4

301	0.23-0.31	Row Middle	3
301	0.31-0.61	Row Middle	3
306	0-0.08	Row	25
306	0.08-0.15	Row	10
306	0.15-0.23	Row	8
306	0.23-0.31	Row	5
306	0.31-0.61	Row	6
306	0-0.08	Row Middle	12
306	0.08-0.15	Row Middle	7
306	0.15-0.23	Row Middle	4
306	0.23-0.31	Row Middle	4
306	0.31-0.61	Row Middle	5
308	0-0.08	Row	12
308	0.08-0.15	Row	7
308	0.15-0.23	Row	5
308	0.23-0.31	Row	3
308	0.31-0.61	Row	3
308	0-0.08	Row Middle	9
308	0.08-0.15	Row Middle	7
308	0.15-0.23	Row Middle	5
308	0.23-0.31	Row Middle	4
308	0.31-0.61	Row Middle	8
309	0-0.08	Row	29
309	0.08-0.15	Row	23
309	0.15-0.23	Row	19
309	0.23-0.31	Row	6
309	0.31-0.61	Row	3
309	0-0.08	Row Middle	11
309	0.08-0.15	Row Middle	7
309	0.15-0.23	Row Middle	6
309	0.23-0.31	Row Middle	4
309	0.31-0.61	Row Middle	4
312	0-0.08	Row	10
312	0.08-0.15	Row	13
312	0.15-0.23	Row	7
312	0.23-0.31	Row	3
312	0.31-0.61	Row	2

312	0-0.08	Row Middle	8
312	0.08-0.15	Row Middle	5
312	0.15-0.23	Row Middle	3
312	0.23-0.31	Row Middle	2
312	0.31-0.61	Row Middle	3
401	0-0.08	Row	21
401	0.08-0.15	Row	8
401	0.15-0.23	Row	5
401	0.23-0.31	Row	3
401	0.31-0.61	Row	4
401	0-0.08	Row Middle	15
401	0.08-0.15	Row Middle	7
401	0.15-0.23	Row Middle	4
401	0.23-0.31	Row Middle	2
401	0.31-0.61	Row Middle	10
402	0-0.08	Row	8
402	0.08-0.15	Row	5
402	0.15-0.23	Row	4
402	0.23-0.31	Row	2
402	0.31-0.61	Row	4
402	0-0.08	Row Middle	8
402	0.08-0.15	Row Middle	5
402	0.15-0.23	Row Middle	3
402	0.23-0.31	Row Middle	2
402	0.31-0.61	Row Middle	4
404	0-0.08	Row	11
404	0.08-0.15	Row	29
404	0.15-0.23	Row	121
404	0.23-0.31	Row	9
404	0.31-0.61	Row	5
404	0-0.08	Row Middle	10
404	0.08-0.15	Row Middle	6
404	0.15-0.23	Row Middle	4
404	0.23-0.31	Row Middle	2
404	0.31-0.61	Row Middle	4
405	0-0.08	Row	9
405	0.08-0.15	Row	12

405	0.15-0.23	Row	7
405	0.23-0.31	Row	4
405	0.31-0.61	Row	3
405	0-0.08	Row Middle	9
405	0.08-0.15	Row Middle	6
405	0.15-0.23	Row Middle	4
405	0.23-0.31	Row Middle	3
405	0.31-0.61	Row Middle	3
411	0-0.08	Row	47
411	0.08-0.15	Row	12
411	0.15-0.23	Row	8
411	0.23-0.31	Row	4
411	0.31-0.61	Row	3
411	0-0.08	Row Middle	17
411	0.08-0.15	Row Middle	8
411	0.15-0.23	Row Middle	5
411	0.23-0.31	Row Middle	3
411	0.31-0.61	Row Middle	11

Table A.15 Additional plot soil sample data and re-sampled plots from Scandia collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

Plot	Depth (m)	Location	P (ppm)
117	0-0.08	Row	11
117	0.08-0.15	Row	5
117	0.15-0.23	Row	6
117	0-0.08	Row Middle	7
117	0.08-0.15	Row Middle	5
117	0.15-0.23	Row Middle	6
120	0-0.08	Row	16
120	0.08-0.15	Row	6
213	0-0.08	Row	16
213	0.08-0.15	Row	6
213	0.15-0.23	Row	6
213	0-0.08	Row Middle	8
213	0.08-0.15	Row Middle	5
213	0.15-0.23	Row Middle	4
214	0-0.08	Row	8
214	0.08-0.15	Row	6
219	0-0.08	Row	12
219	0.08-0.15	Row	6
220	0-0.08	Row	17
220	0.08-0.15	Row	8
304	0-0.08	Row	15
304	0.08-0.15	Row	7
304	0.15-0.23	Row	9
304	0-0.08	Row Middle	13
304	0.08-0.15	Row Middle	5
304	0.15-0.23	Row Middle	4
308	0-0.08	Row	26
308	0.08-0.15	Row	6
401	0-0.08	Row Middle	14
401	0.08-0.15	Row Middle	6
403	0-0.08	Row	24
403	0.08-0.15	Row	8
403	0.15-0.23	Row	5
403	0-0.08	Row Middle	12

403	0.08-0.15	Row Middle	7
403	0.15-0.23	Row Middle	4
404	0-0.08	Row	11
404	0.08-0.15	Row	57
404	0.15-0.23	Row	91
411	0-0.08	Row Middle	12
411	0.08-0.15	Row Middle	5

Ottawa – East Central Kansas Experiment Field

P Management in Reduced Tillage (Ottawa, KS)

Plot length = 40 ft, Alley = 30 ft

N

Trt.	Starter P	Broadcast P	Deep Band P	Total P	Broadcast P	Total P
	Corn				Soybeans	
1	0	0	0	0	0	0
2	20	0	0	20	0	0
3	0	40	0	40	0	0
4	20	20	0	40	0	0
5	0	0	40	40	0	0
6	20	0	20	40	0	0
7	0	80	0	80	0	0
8	20	60	0	80	0	0
9	0	0	80	80	0	0
10	20	0	60	80	0	0
11	20	60	0	80	40	40
12	20	0	60	80	40	40
13	0	40 (tilled)	0	40	0	0

B	401	402	403	404	405	406	407	408	409	410	411	412	413	B	B	414	415	416	417	418	419	420	421	422	423	424	425	426	B
	8	2	13	11	1	5	10	6	7	4	3	12	9			6	9	8	3	12	7	2	5	1	11	4	10	13	

Soybeans (even years) Corn (odd years) Corn (even years) Soybeans (odd years)

B	301	302	303	304	305	306	307	308	309	310	311	312	313	B	B	314	315	316	317	318	319	320	321	322	323	324	325	326	B
	13	12	1	10	5	11	2	9	4	3	8	7	6			1	9	6	3	7	11	4	12	5	2	8	10	13	

Soybeans (even years) Corn (odd years) Corn (even years) Soybeans (odd years)

B	201	202	203	204	205	206	207	208	209	210	211	212	213	B	B	214	215	216	217	218	219	220	221	222	223	224	225	226	B
	13	12	2	11	1	5	8	4	7	9	10	3	6			13	5	4	10	7	8	1	9	12	3	11	6	2	

Soybeans (even years) Corn (odd years) Corn (even years) Soybeans (odd years)

B	101	102	103	104	105	106	107	108	109	110	111	112	113	B	B	114	115	116	117	118	119	120	121	122	123	124	125	126	B
	11	10	4	12	7	13	3	8	6	2	5	9	1			9	6	7	12	10	1	2	13	8	3	5	4	11	

Soybeans (even years) Corn (odd years) Corn (even years) Soybeans (odd years)

Table A.16 Corn tissue nutrient analysis and biomass yield data from Ottawa in the 2006 growing season.

Plot	--------------Ear Leaf-------------			---------------------Stover (black layer)---------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	(kg $15plnt^{-1}$)
114	2.61	0.204	0.74	0.78	0.070	0.63	1.07
115	2.63	0.284	0.64	1.04	0.100	0.44	1.47
116	2.58	0.226	0.77	0.76	0.060	0.65	1.20
117	2.56	0.188	0.86	0.60	0.060	0.52	1.16
118	2.54	0.203	0.71	0.85	0.080	0.52	1.19
119	2.55	0.240	0.63	0.61	0.040	0.59	1.02
120	2.40	0.148	0.85	0.72	0.060	0.69	1.12
121	2.32	0.155	0.93	0.71	0.070	0.79	1.05
122	2.67	0.204	0.91	0.78	0.090	0.60	1.11
123	2.58	0.210	0.85	0.71	0.060	0.66	1.10
124	2.52	0.180	0.84	0.69	0.050	0.50	1.02
125	2.62	0.241	0.62	0.70	0.060	0.67	1.12
126	2.47	0.203	0.75	0.88	0.090	0.81	1.13
214	2.56	0.191	0.85	0.56	0.040	0.61	1.08
215	2.73	0.228	0.99	0.66	0.050	0.69	1.00
216	2.58	0.206	0.78	0.54	0.030	0.63	1.09
217	2.63	0.207	0.90	0.94	0.080	0.59	1.03
218	2.73	0.304	0.56	0.61	0.060	0.59	1.29
219	2.65	0.224	0.75	0.56	0.050	0.53	1.05
220	2.67	0.222	0.71	0.78	0.040	0.65	0.94
221	2.42	0.149	0.79	0.79	0.060	0.49	1.08
222	2.53	0.271	0.63	0.77	0.090	0.67	1.25
223	2.53	0.224	0.79	0.73	0.050	0.64	0.83
224	2.75	0.206	0.83	0.70	0.050	0.50	0.73
225	2.40	0.185	0.59	0.73	0.060	0.56	1.03
226	2.70	0.228	0.62	0.54	0.030	0.63	1.03
314	2.76	0.212	0.80	0.75	0.050	0.67	0.94
315	2.67	0.163	0.95	0.66	0.050	0.61	1.23
316	2.72	0.249	0.79	0.71	0.060	0.79	1.26
317	2.80	0.240	0.87	0.66	0.040	0.61	1.10
318	2.70	0.207	0.72	0.76	0.060	0.54	1.08
319	2.69	0.216	0.70	0.58	0.040	0.54	0.96
320	2.62	0.181	0.77	0.68	0.040	0.54	1.08
321	2.70	0.180	0.86	0.48	0.030	0.48	1.03
322	2.63	0.208	0.81	0.73	0.060	0.46	0.94

323	2.78	0.233	0.67	0.68	0.050	0.48	1.04
324	2.59	0.181	0.66	0.62	0.050	0.45	0.93
325	2.64	0.224	0.65	0.77	0.060	0.49	0.74
326	2.74	0.320	0.52	0.58	0.040	0.45	0.94
414	2.72	0.221	0.74	0.79	0.070	0.68	1.14
415	2.89	0.251	1.00	0.64	0.070	0.68	1.00
416	2.96	0.300	1.05	0.47	0.050	1.01	1.17
417	2.77	0.230	1.02	0.59	0.050	0.90	0.92
418	2.73	0.208	0.98	0.71	0.060	0.77	0.90
419	2.92	0.222	0.86	0.72	0.050	0.53	0.75
420	2.57	0.179	0.83	0.62	0.030	0.58	0.92
421	2.58	0.164	0.77	0.72	0.050	0.50	0.88
422	2.73	0.235	0.59	0.62	0.030	0.56	0.80
423	2.59	0.156	0.84	0.67	0.040	0.49	0.92
424	2.71	0.196	0.65	0.85	0.070	0.61	0.82
425	2.70	0.190	0.69	0.76	0.050	0.52	0.74
426	2.95	0.338	0.55	0.76	0.060	0.58	0.99

Table A.17 Corn grain yield and nutrient analysis data from Ottawa in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	---------------------Grain---------------------		
					N (%)	P (%)	K (%)
114	12.19	10.70	15.1	25.76	1.44	0.255	0.28
115	12.19	11.43	14.9	19.05	1.46	0.254	0.28
116	12.19	12.06	14.8	21.77	1.47	0.256	0.30
117	12.19	13.02	15.0	22.27	1.39	0.234	0.26
118	12.19	11.52	14.8	25.44	1.46	0.260	0.28
119	12.19	10.34	14.6	21.18	1.50	0.222	0.28
120	12.19	9.57	14.5	21.77	1.44	0.241	0.29
121	12.19	11.93	14.5	24.13	1.40	0.226	0.26
122	12.19	11.25	14.6	23.94	1.39	0.247	0.27
123	12.19	11.07	14.9	23.94	1.53	0.257	0.29
124	12.19	11.52	14.9	25.44	1.51	0.254	0.27
125	12.19	10.79	14.9	21.68	1.45	0.262	0.29
126	12.19	10.34	14.6	24.44	1.50	0.273	0.29
214	12.19	12.65	15.1	25.17	1.49	0.261	0.29
215	12.19	12.70	15.2	21.54	1.50	0.254	0.29
216	12.19	12.43	14.3	22.86	1.43	0.215	0.24
217	12.19	9.93	14.9	23.85	1.50	0.288	0.30
218	12.19	11.16	14.5	22.81	1.46	0.277	0.30
219	12.19	11.61	14.4	23.99	1.45	0.262	0.30
220	12.19	9.21	14.3	23.04	1.46	0.224	0.28
221	12.19	11.43	14.7	23.13	1.47	0.267	0.30
222	12.19	11.79	14.3	24.26	1.43	0.318	0.35
223	12.19	11.02	14.1	22.99	1.50	0.230	0.27
224	12.19	10.79	14.2	22.54	1.48	0.267	0.31
225	12.19	10.48	14.4	23.22	1.49	0.256	0.30
226	12.19	10.93	15.1	24.58	1.44	0.253	0.31
314	12.19	9.12	15.1	23.81	1.54	0.241	0.29
315	12.19	11.84	14.1	22.13	1.54	0.286	0.29
316	12.19	12.43	14.7	23.45	1.52	0.276	0.31
317	12.19	10.29	14.5	21.77	1.52	0.260	0.30
318	12.19	11.29	15.0	25.76	1.52	0.280	0.30
319	12.19	10.43	14.5	24.76	1.49	0.247	0.30
320	12.19	10.16	14.8	23.94	1.50	0.229	0.27
321	12.19	11.75	14.6	23.94	1.42	0.245	0.27
322	12.19	10.39	14.5	22.45	1.51	0.288	0.32

323	12.19	10.48	14.8	22.63	1.52	0.234	0.28
324	12.19	10.88	14.6	22.54	1.47	0.256	0.28
325	12.19	10.52	14.7	23.22	1.48	0.290	0.32
326	12.19	11.70	14.9	24.58	1.43	0.235	0.28
414	12.19	12.47	14.8	21.81	1.51	0.286	0.33
415	12.19	13.11	14.2	24.31	1.49	0.307	0.31
416	12.19	12.52	14.9	21.59	1.44	0.296	0.32
417	12.19	12.02	14.7	22.86	1.44	0.254	0.29
418	12.19	11.29	15.0	25.49	1.42	0.233	0.29
419	12.19	11.61	14.6	23.08	1.42	0.233	0.29
420	12.19	9.34	14.6	23.63	1.50	0.217	0.28
421	12.19	10.61	13.9	20.41	1.47	0.249	0.29
422	12.19	8.98	14.4	21.54	1.49	0.197	0.28
423	12.19	10.11	13.9	21.99	1.53	0.230	0.29
424	12.19	9.66	14.5	23.63	1.43	0.227	0.28
425	12.19	9.16	14.1	22.81	1.46	0.244	0.28
426	12.19	10.97	14.5	22.54	1.44	0.232	0.26

Table A.18 Soybean tissue nutrient analysis data from Ottawa in the 2006 growing season.

Plot	---------------------------------------Trifoliates (R3)---------------------------------------		
	N (%)	P (%)	K (%)
101	4.70	0.358	1.47
102	5.54	0.391	1.48
103	5.44	0.375	1.51
104	5.08	0.360	1.47
105	5.27	0.363	1.53
106	4.73	0.297	1.43
107	5.11	0.336	1.53
108	5.12	0.347	1.47
109	5.05	0.327	1.50
110	5.32	0.336	1.42
111	5.36	0.347	1.49
112	5.17	0.312	1.31
113	5.38	0.292	1.31
201	5.88	0.424	1.63
202	5.39	0.368	1.34
203	5.35	0.387	1.68
204	5.16	0.379	1.60
205	5.40	0.376	1.59
206	5.49	0.359	1.60
207	5.31	0.362	1.46
208	5.48	0.396	1.42
209	5.25	0.311	1.41
210	5.59	0.345	1.68
211	5.53	0.316	1.50
212	5.34	0.335	1.49
213	4.72	0.302	1.25
301	5.43	0.379	1.48
302	5.41	0.374	1.48
303	5.07	0.358	1.59
304	5.31	0.338	1.71
305	5.29	0.332	1.64
306	5.43	0.332	1.55
307	5.25	0.308	1.57
308	5.23	0.283	1.44
309	5.45	0.335	1.47
310	5.33	0.306	1.56
311	5.30	0.331	1.51

312	5.21	0.311	1.45
313	5.13	0.287	1.35
401	5.17	0.324	1.52
402	5.43	0.334	1.64
403	5.31	0.369	1.84
404	5.50	0.378	1.78
405	5.27	0.321	1.59
406	5.10	0.314	1.71
407	5.25	0.301	1.70
408	5.35	0.290	1.39
409	5.28	0.297	1.53
410	5.30	0.317	1.40
411	5.35	0.282	1.50
412	5.32	0.320	1.36
413	5.25	0.301	1.40

Table A.19 Soybean grain yield and nutrient analysis data from Ottawa in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	---------------------Grain---------------------		
				N (%)	P (%)	K (%)
101	12.19	5.08	11.8	5.53	0.528	1.67
102	12.19	5.53	11.6	5.59	0.497	1.76
103	12.19	5.44	11.6	5.36	0.488	1.74
104	12.19	5.26	11.7	5.31	0.49	1.71
105	12.19	4.99	11.5	5.56	0.443	1.71
106	12.19	5.49	11.4	5.46	0.422	1.68
107	12.19	5.26	11.4	5.58	0.444	1.68
108	12.19	5.44	11.5	5.44	0.454	1.68
109	12.19	5.35	11.8	5.68	0.431	1.68
110	12.19	5.35	11.5	5.18	0.404	1.65
111	12.19	5.12	11.4	5.13	0.382	1.60
112	12.19	5.22	11.6	5.91	0.462	1.69
113	12.19	5.4	11.7	5.91	0.458	1.65
201	12.19	4.99	11.3	5.61	0.559	1.71
202	12.19	5.53	11.6	5.71	0.558	1.74
203	12.19	5.35	11.4	5.13	0.438	1.63
204	12.19	5.03	11.4	5.32	0.488	1.71
205	12.19	5.08	11.4	5.50	0.447	1.69
206	12.19	5.08	11.5	5.43	0.444	1.61
207	12.19	5.03	11.3	5.67	0.473	1.68
208	12.19	5.35	11.5	5.82	0.484	1.68
209	12.19	5.17	11.5	5.94	0.425	1.67
210	12.19	5.26	11.9	5.66	0.431	1.70
211	12.19	5.71	11.6	5.69	0.411	1.68
212	12.19	5.62	11.5	5.59	0.412	1.64
213	12.19	5.17	11.9	5.57	0.416	1.61
301	12.19	5.44	11.5	5.59	0.508	1.68
302	12.19	5.49	11.8	5.93	0.568	1.76
303	12.19	5.31	11.4	5.77	0.509	1.72
304	12.19	5.03	11.3	5.15	0.436	1.65
305	12.19	4.9	11.4	5.56	0.456	1.67
306	12.19	5.62	11.4	5.48	0.462	1.71
307	12.19	5.35	11.2	5.64	0.423	1.71
308	12.19	5.4	11.5	5.62	0.41	1.70
309	12.19	5.53	11.5	5.71	0.459	1.70

310	12.19	5.58	11.4	5.56	0.416	1.67
311	12.19	5.76	11.8	5.50	0.43	1.62
312	12.19	5.53	12.2	5.62	0.422	1.67
313	12.19	5.26	11.7	6.06	0.425	1.68
401	12.19	5.44	11.8	5.74	0.502	1.72
402	12.19	5.8	11.8	5.75	0.474	1.72
403	12.19	5.53	11.5	5.33	0.457	1.74
404	12.19	5.53	11.4	5.44	0.494	1.76
405	12.19	5.17	11.3	5.38	0.408	1.69
406	12.19	5.31	11.7	5.37	0.403	1.66
407	12.19	5.4	10.9	5.68	0.396	1.73
408	12.19	5.35	11.3	5.13	0.375	1.62
409	12.19	5.12	11.6	5.71	0.42	1.70
410	12.19	5.4	11.8	5.76	0.451	1.70
411	12.19	5.22	11.7	5.69	0.408	1.68
412	12.19	5.67	11.8	5.95	0.464	1.66
413	12.19	4.9	11.7	5.79	0.412	1.66

Table A.20 Corn tissue nutrient analysis and biomass yield data from Ottawa in the 2007 growing season.

Plot	------------------Ear Leaf------------------			-------------------------Stover (V5)-------------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	(kg $15plnt^{-1}$)
101	3.97	0.407	1.68	3.97	0.407	1.68	0.078
102	3.89	0.443	1.72	3.89	0.443	1.72	0.084
103	4.38	0.417	1.88	4.38	0.417	1.88	0.104
104	4.50	0.446	2.07	4.50	0.446	2.07	0.086
105	4.09	0.391	1.68	4.09	0.391	1.68	0.089
106	4.02	0.420	1.99	4.02	0.420	1.99	0.097
107	4.32	0.404	1.78	4.32	0.404	1.78	0.108
108	4.69	0.487	1.70	4.69	0.487	1.70	0.078
109	4.24	0.481	1.98	4.24	0.481	1.98	0.092
110	4.33	0.417	1.72	4.33	0.417	1.72	0.078
111	4.35	0.462	1.73	4.35	0.462	1.73	0.091
112	4.69	0.465	1.61	4.69	0.465	1.61	0.100
113	4.29	0.401	2.39	4.29	0.401	2.39	0.093
201	4.09	0.437	1.82	4.09	0.437	1.82	0.094
202	3.87	0.434	1.98	3.87	0.434	1.98	0.083
203	4.20	0.453	2.28	4.20	0.453	2.28	0.084
204	4.37	0.458	2.03	4.37	0.458	2.03	0.075
205	4.44	0.400	2.19	4.44	0.400	2.19	0.093
206	4.17	0.432	1.89	4.17	0.432	1.90	0.098
207	4.34	0.457	1.94	4.34	0.457	1.94	0.109
208	3.66	0.398	1.87	3.66	0.398	1.87	0.088
209	4.30	0.424	1.85	4.30	0.424	1.85	0.084
210	3.76	0.413	2.02	3.77	0.413	2.02	0.087
211	4.16	0.476	1.66	4.16	0.476	1.66	0.087
212	4.04	0.392	2.13	4.04	0.392	2.13	0.098
213	4.05	0.463	1.67	4.05	0.463	1.67	0.080
301	4.17	0.408	2.34	4.17	0.408	2.34	0.075
302	4.69	0.469	1.99	4.69	0.469	1.99	0.085
303	4.28	0.410	2.20	4.28	0.410	2.20	0.091
304	4.51	0.456	1.85	4.52	0.456	1.85	0.089
305	4.19	0.413	2.27	4.19	0.413	2.27	0.091
306	4.62	0.441	1.69	4.62	0.441	1.70	0.083
307	3.92	0.384	2.24	3.92	0.384	2.24	0.084
308	4.47	0.466	1.92	4.47	0.466	1.93	0.101
309	4.70	0.469	1.93	4.70	0.469	1.93	0.092

310	4.01	0.396	2.02	4.01	0.396	2.02	0.082
311	4.05	0.425	1.83	4.05	0.425	1.83	0.104
312	4.07	0.410	2.11	4.07	0.410	2.11	0.094
313	4.32	0.463	1.70	4.32	0.463	1.70	0.113
401	4.08	0.407	2.14	4.08	0.407	2.14	0.083
402	4.27	0.447	1.92	4.27	0.447	1.92	0.104
403	4.26	0.438	2.75	4.26	0.438	2.75	0.108
404	4.00	0.402	2.20	4.01	0.402	2.20	0.112
405	4.00	0.404	2.50	4.00	0.404	2.50	0.114
406	4.44	0.421	1.76	4.44	0.421	1.76	0.117
407	4.27	0.498	1.77	4.27	0.498	1.77	0.140
408	3.81	0.420	1.73	3.81	0.420	1.73	0.108
409	4.12	0.380	1.86	4.12	0.380	1.86	0.111
410	4.34	0.440	1.45	4.34	0.440	1.45	0.108
411	4.54	0.382	1.68	4.54	0.382	1.68	0.108
412	4.48	0.497	1.63	4.48	0.497	1.63	0.122
413	4.04	0.428	1.53	4.04	0.428	1.53	0.113

Table A.19 Continued.

Plot	--------------------------------------Stover (Black Layer)---			
	N	P	K	Dry Weight
	(%)	(%)	(%)	(kg 15plnt^{-1})
101	0.41	0.048	0.78	0.533
102	0.48	0.063	0.82	0.561
103	0.51	0.052	0.70	0.433
104	0.36	0.037	0.94	0.574
105	0.33	0.030	0.70	0.402
106	0.33	0.030	0.74	0.367
107	0.62	0.045	0.85	0.217
108	0.47	0.050	0.77	0.544
109	0.95	0.067	1.53	0.331
110	0.65	0.045	1.08	0.465
111	0.99	0.069	1.04	0.433
112	0.51	0.046	0.87	0.526
113	0.36	0.035	0.70	0.214
201	0.45	0.061	0.89	.
202	0.43	0.051	0.72	0.476
203	0.49	0.037	0.75	0.459
204	0.48	0.038	0.85	0.592
205	0.44	0.027	1.05	0.219
206	0.35	0.029	0.86	0.331
207	0.50	0.034	0.81	0.271
208	0.50	0.036	0.59	0.502
209	0.54	0.034	0.71	0.367
210	0.47	0.038	0.79	0.428
211	0.43	0.048	1.01	0.660
212	0.48	0.034	0.89	0.388
213	0.45	0.032	0.73	0.429
301	0.36	0.039	0.75	0.409
302	0.38	0.043	0.90	0.411
303	0.49	0.032	0.92	0.380
304	0.35	0.037	0.94	0.428
305	0.33	0.030	0.76	0.280
306	0.41	0.038	0.79	0.419
307	0.41	0.029	0.73	0.441
308	0.47	0.036	0.71	0.377
309	0.48	0.039	0.70	0.356
310	0.37	0.023	0.49	0.444

311	0.38	0.047	0.69	0.406
312	0.34	0.028	0.70	0.264
313	0.43	0.031	0.65	0.455
401	0.40	0.046	0.71	0.349
402	0.41	0.033	0.73	0.529
403	0.63	0.055	1.01	0.336
404	0.40	0.032	0.86	0.378
405	0.36	0.022	0.67	0.275
406	0.52	0.043	0.78	0.303
407	0.46	0.050	0.79	0.363
408	0.33	0.032	0.77	0.235
409	0.41	0.031	0.81	0.214
410	0.60	0.036	0.81	0.230
411	0.34	0.024	0.69	0.257
412	0.34	0.026	0.57	0.316
413	0.40	0.030	0.96	0.294

Table A.21 Corn grain yield and nutrient analysis data from Ottawa in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	---------------------Grain---------------------		
					N (%)	P (%)	K (%)
101	12.19	12.70	16.8	54.8	1.22	0.215	0.27
102	12.19	12.97	15.8	55.0	1.14	0.247	0.32
103	12.19	12.97	16.4	54.9	1.11	0.188	0.24
104	12.19	11.88	16.4	54.1	1.11	0.178	0.24
105	12.19	11.57	16.5	55.0	1.05	0.223	0.31
106	12.19	12.07	16.5	54.2	1.17	0.213	0.29
107	12.19	11.79	16.9	53.5	1.09	0.187	0.26
108	12.19	11.43	16.3	54.4	1.27	0.257	0.35
109	12.19	12.61	16.3	54.3	1.29	0.219	0.32
110	12.19	11.61	16.3	53.9	1.17	0.148	0.22
111	12.19	12.93	15.8	54.3	1.20	0.189	0.24
112	12.19	12.47	15.8	54.4	1.20	0.212	0.26
113	12.19	11.61	17.1	53.2	1.27	0.227	0.32
201	11.19	10.93	16.2	55.2	1.17	0.267	0.30
202	11.19	10.75	16.0	55.0	1.38	0.323	0.41
203	11.19	11.43	15.9	54.1	1.35	0.276	0.35
204	11.19	10.25	16.1	54.7	1.42	0.378	0.46
205	11.19	9.53	16.3	53.6	1.37	0.204	0.29
206	11.19	10.52	16.3	53.9	1.24	0.231	0.30
207	11.19	11.39	15.8	53.8	1.39	0.278	0.37
208	11.19	11.61	15.8	54.5	1.43	0.257	0.32
209	11.19	10.52	15.9	53.0	1.35	0.318	0.43
210	11.19	10.34	16.1	54.3	1.24	0.318	0.40
211	11.19	10.48	15.3	53.8	1.32	0.296	0.37
212	11.19	10.39	16.7	53.4	1.38	0.349	0.49
213	11.19	11.70	16.5	54.0	1.46	0.231	0.32
301	12.19	12.66	16.4	54.1	1.15	0.198	0.25
302	12.19	12.52	16.1	53.8	1.40	0.390	0.47
303	12.19	11.93	16.1	53.7	1.37	0.235	0.34
304	12.19	10.89	16.0	54.3	1.35	0.251	0.33
305	12.19	11.02	16.3	54.3	1.37	0.267	0.34
306	12.19	12.20	15.9	54.7	1.40	0.303	0.40
307	12.19	11.66	16.4	53.4	1.51	0.295	0.41
308	12.19	12.34	16.1	54.5	1.29	0.199	0.26
309	12.19	12.02	16.1	53.8	1.49	0.338	0.44

310	12.19	11.16	16.3	53.4	1.39	0.216	0.30
311	12.19	12.02	16.0	53.8	1.39	0.264	0.36
312	12.19	12.02	16.5	53.9	1.40	0.248	0.34
313	12.19	12.70	16.2	54.2	1.45	0.265	0.38
401	12.19	12.75	16.0	54.9	1.42	0.300	0.38
402	12.19	12.47	16.1	54.8	1.46	0.287	0.39
403	12.19	12.25	16.0	54.5	1.38	0.252	0.35
404	12.19	12.02	15.7	54.2	1.40	0.306	0.39
405	12.19	10.70	17.1	52.8	1.41	0.268	0.37
406	12.19	13.34	16.3	54.1	1.28	0.244	0.33
407	12.19	11.97	15.9	54.5	1.21	0.217	0.31
408	12.19	11.57	16.0	54.6	1.21	0.217	0.30
409	12.19	11.88	16.3	53.6	1.33	0.316	0.42
410	12.19	10.93	16.2	54.3	1.50	0.281	0.39
411	12.19	11.07	16.4	53.4	1.45	0.283	0.40
412	12.19	12.25	16.4	54.3	1.48	0.245	0.33
413	12.19	12.61	16.2	54.4	1.34	0.244	0.33

Table A.22 Soybean tissue nutrient analysis data from Ottawa in the 2007 growing season.

Plot	--------------------Trifoliates (V4)----------------------			---------------------Trifoliates (R3)---------------------		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
114	4.12	0.33	1.17	2.98	0.17	0.63
115	4.04	0.32	1.27	3.24	0.17	0.71
116	4.20	0.35	1.29	3.16	0.17	0.75
117	4.31	0.36	1.26	3.17	0.19	0.73
118	4.33	0.35	1.24	2.96	0.17	0.75
119	4.18	0.33	1.28	3.08	0.16	0.87
120	4.27	0.37	1.31	2.99	0.17	0.82
121	4.19	0.36	1.21	3.25	0.17	0.72
122	4.30	0.37	1.39	3.13	0.17	0.80
123	4.13	0.33	1.20	3.10	0.17	0.70
124	4.53	0.36	1.25	2.98	0.17	0.66
125	4.82	0.37	1.36	3.24	0.19	0.66
126	4.53	0.35	1.21	2.96	0.18	0.63
214	4.43	0.35	1.29	2.93	0.15	0.67
215	4.41	0.33	1.41	3.24	0.18	0.66
216	4.38	0.34	1.32	3.03	0.17	0.60
217	4.89	0.36	1.28	3.11	0.18	0.63
218	4.56	0.34	1.26	3.21	0.17	0.63
219	5.08	0.38	1.40	2.95	0.16	0.62
220	4.93	0.35	1.23	3.02	0.16	0.72
221	4.72	0.34	1.20	3.21	0.17	0.64
222	4.62	0.36	1.32	3.14	0.17	0.68
223	4.77	0.36	1.22	3.20	0.17	0.68
224	4.73	0.36	1.19	3.22	0.18	0.60
225	4.79	0.34	1.25	3.35	0.18	0.59
226	4.69	0.34	1.21	3.30	0.17	0.60
314	4.65	0.33	1.47	3.21	0.16	0.73
315	4.53	0.31	1.17	3.55	0.18	0.68
316	4.57	0.34	1.16	3.51	0.19	0.64
317	4.79	0.37	1.27	3.09	0.16	0.66
318	4.82	0.36	1.14	3.35	0.18	0.70
319	4.58	0.37	1.18	3.60	0.18	0.74
320	4.67	0.34	1.19	3.48	0.17	0.81
321	4.55	0.33	1.08	3.22	0.18	0.74
322	4.71	0.34	1.16	3.41	0.19	0.79
323	4.74	0.35	1.22	3.44	0.19	0.69
324	4.71	0.34	1.14	3.40	0.20	0.66

325	4.81	0.35	1.08	3.15	0.20	0.64
326	4.51	0.31	1.07	3.12	0.16	0.72
414	4.30	0.35	1.58	3.42	0.19	0.78
415	4.46	0.34	1.40	3.30	0.19	0.80
416	4.23	0.35	1.52	3.34	0.19	0.76
417	4.14	0.35	1.45	3.08	0.17	0.83
418	3.92	0.33	1.24	3.05	0.16	0.70
419	4.30	0.35	1.43	3.28	0.15	0.76
420	4.51	0.35	1.23	3.42	0.16	0.73
421	4.52	0.33	1.17	3.34	0.16	0.66
422	4.73	0.34	1.31	3.31	0.16	0.74
423	4.84	0.37	1.23	3.26	0.17	0.65
424	4.79	0.35	1.15	3.44	0.17	0.67
425	4.64	0.36	1.16	3.38	0.20	0.62
426	4.58	0.34	1.29	3.23	0.17	0.67

Table A.23 Soybean grain yield and nutrient analysis data from Ottawa in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	---------------------Grain---------------------		
				N (%)	P (%)	K (%)
114	12.19	2.05	11.6	5.20	0.488	1.63
115	12.19	2.23	11.7	5.64	0.495	1.69
116	12.19	2.36	12.1	5.63	0.500	1.65
117	12.19	1.95	12.3	5.50	0.515	1.65
118	12.19	2.00	12.3	6.18	0.538	1.75
119	12.19	2.27	12.6	5.87	0.498	1.73
120	12.19	2.18	11.8	5.95	0.486	1.69
121	12.19	2.36	12.2	6.24	0.497	1.73
122	12.19	2.50	12.2	5.93	0.550	1.76
123	12.19	2.45	12.4	5.92	0.502	1.70
124	12.19	2.41	12.2	5.69	0.532	1.72
125	12.19	2.27	12.1	5.94	0.538	1.63
126	12.19	2.41	12.3	5.62	0.536	1.74
214	12.19	2.59	12.0	5.44	0.495	1.67
215	12.19	2.32	12.1	5.74	0.525	1.69
216	12.19	2.73	12.0	5.80	0.512	1.64
217	12.19	2.91	12.4	5.79	0.532	1.67
218	12.19	2.45	12.1	7.14	0.534	1.69
219	12.19	2.32	12.0	5.77	0.501	1.63
220	12.19	2.27	12.0	5.92	0.469	1.64
221	12.19	2.27	11.9	6.01	0.636	1.72
222	12.19	2.68	12.0	5.62	0.501	1.65
223	12.19	2.59	12.1	5.81	0.489	1.67
224	12.19	2.41	11.9	5.61	0.519	1.63
225	12.19	2.45	12.0	6.03	0.552	1.66
226	12.19	2.45	12.3	5.79	0.553	1.70
314	12.19	2.45	11.9	5.76	0.476	1.67
315	12.19	3.00	12.4	5.62	0.549	1.66
316	12.19	2.86	12.1	5.93	0.532	1.70
317	12.19	2.68	12.5	5.68	0.504	1.64
318	12.19	2.36	12.2	5.80	0.521	1.60
319	12.19	2.09	12.0	6.15	0.522	1.63
320	12.19	2.05	12.3	5.94	0.473	1.63
321	12.19	2.05	12.3	6.03	0.504	1.63
322	12.19	2.36	12.4	6.05	0.521	1.65

323	12.19	2.45	12.6	5.91	0.509	1.58
324	12.19	2.41	12.0	5.66	0.530	1.59
325	12.19	2.55	12.4	5.70	0.529	1.56
326	12.19	2.50	12.4	5.83	0.483	1.63
414	12.19	2.95	12.4	5.92	0.542	1.68
415	12.19	3.41	12.7	5.61	0.584	1.74
416	12.19	3.09	12.6	5.67	0.559	1.76
417	12.19	2.77	12.6	5.77	0.505	1.71
418	12.19	2.55	12.5	6.10	0.533	1.73
419	12.19	2.14	12.0	5.73	0.458	1.60
420	12.19	2.50	12.4	5.73	0.432	1.58
421	12.19	2.73	12.6	6.25	0.488	1.63
422	12.19	2.41	12.4	5.95	0.447	1.59
423	12.19	2.64	12.6	6.09	0.509	1.63
424	12.19	2.45	12.5	6.03	0.471	1.63
425	12.19	2.73	12.3	6.37	0.529	1.64
426	12.19	2.50	12.2	6.08	0.467	1.59

Table A.24 Corn tissue nutrient analysis and biomass yield data from Ottawa in the 2008 growing season.

Plot	Ear Leaf	-------------Stover (V5)--------------	
	P	P	Dry Weight
	(%)	(%)	(kg 15plnt^{-1})
114	0.339	0.397	0.209
115	0.268	0.397	0.215
116	0.266	0.341	0.196
117	0.272	0.389	0.228
118	0.293	0.438	0.223
119	0.228	0.330	0.203
120	0.243	0.364	0.207
121	0.253	0.403	0.199
122	0.290	0.415	0.202
123	0.263	0.398	0.203
124	0.269	0.387	0.196
125	0.275	0.418	0.225
126	0.303	0.423	0.252
214	0.273	0.385	0.212
215	0.311	0.358	0.209
216	0.280	0.389	0.215
217	0.342	0.426	0.231
218	0.308	0.376	0.209
219	0.325	0.439	0.242
220	0.239	0.393	0.184
221	0.325	0.410	0.214
222	0.280	0.386	0.230
223	0.290	0.390	0.196
224	0.309	0.459	0.211
225	0.302	0.375	0.197
226	0.243	0.309	0.215
314	0.220	0.269	0.200
315	0.387	0.363	0.207
316	0.319	0.341	0.227
317	0.247	0.384	0.209
318	0.321	0.314	0.212
319	0.352	0.321	0.214
320	0.305	0.311	0.226
321	0.323	0.325	0.201
322	0.329	0.338	0.186

323	0.278	0.430	0.207
324	0.344	0.430	0.194
325	0.370	0.349	0.225
326	0.256	0.263	0.223
414	0.314	0.280	0.266
415	0.352	0.336	0.227
416	0.319	0.355	0.230
417	0.316	0.326	0.201
418	0.288	0.370	0.248
419	0.292	0.324	0.195
420	0.283	0.373	0.202
421	0.302	0.327	0.202
422	0.237	0.309	0.177
423	0.299	0.307	0.200
424	0.276	0.343	0.232
425	0.351	0.366	0.215
426	0.254	0.307	0.203

Table A.25 Corn grain yield and nutrient analysis data from Ottawa in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
114	12.19	8.54	16.3	25.1	0.297
115	12.19	14.03	16.5	25.4	0.290
116	12.19	15.48	16.7	25.0	0.278
117	12.19	18.80	16.2	25.7	0.243
118	12.19	14.57	16.6	24.8	0.292
119	12.19	14.16	16.9	25.2	0.199
120	12.19	15.57	16.7	25.1	0.236
121	12.19	16.62	16.9	25.0	0.241
122	12.19	16.16	16.9	25.3	0.275
123	12.19	14.71	16.6	24.9	0.283
124	12.19	17.71	17.1	25.2	0.259
125	12.19	17.21	16.7	24.8	0.271
126	12.19	13.76	16.9	24.8	0.311
214	11.19	17.30	16.8	25.3	0.259
215	11.19	17.98	16.4	25.4	0.244
216	11.19	18.43	16.9	24.6	0.284
217	11.19	16.89	16.5	25.5	0.293
218	11.19	17.48	16.6	25.4	0.321
219	11.19	16.89	16.7	25.2	0.279
220	11.19	15.16	17.0	25.2	0.211
221	11.19	17.43	17.2	25.2	0.271
222	11.19	16.62	16.5	25.3	0.326
223	11.19	15.44	16.8	25.4	0.295
224	11.19	16.30	16.4	25.6	0.283
225	11.19	15.84	16.5	25.4	0.269
226	11.19	15.98	16.4	24.7	0.226
314	12.19	15.71	17.0	24.8	0.195
315	12.19	17.30	16.9	25.7	0.220
316	12.19	17.93	16.6	25.2	0.252
317	12.19	17.93	16.9	25.2	0.229
318	12.19	16.98	16.5	25.0	0.300
319	12.19	17.52	16.8	25.4	0.272
320	12.19	17.21	16.1	25.0	0.240
321	12.19	16.48	16.5	25.6	0.287
322	12.19	17.03	16.8	25.1	0.249
323	12.19	16.75	16.1	25.5	0.215

324	12.19	15.07	16.5	25.6	0.296
325	12.19	16.21	16.4	25.0	0.255
326	12.19	16.43	16.6	25.0	0.239
414	12.19	17.30	16.6	25.5	0.262
415	12.19	19.02	16.7	25.0	0.276
416	12.19	18.07	16.8	25.2	0.245
417	12.19	17.84	16.2	25.2	0.271
418	12.19	17.30	16.2	25.1	0.264
419	12.19	16.71	16.6	25.3	0.307
420	12.19	17.03	16.6	25.2	0.229
421	12.19	16.84	16.6	25.5	0.235
422	12.19	15.39	16.7	25.0	0.275
423	12.19	16.98	16.1	23.7	0.248
424	12.19	17.52	16.0	25.2	0.254
425	12.19	16.39	16.6	24.9	0.245
426	12.19	16.07	16.6	25.3	0.241

Table A.26 Soybean tissue nutrient analysis and biomass yield data from Ottawa in the 2008 growing season.

Plot	---------------------------------Stover (V4)---------------------------------		Trifoliates (R3)
	P (%)	Dry Weight (kg 15plnt^{-1})	P (%)
101	0.321	0.074	0.388
102	0.338	0.070	0.392
103	0.319	0.065	0.452
104	0.349	0.064	0.406
105	0.321	0.065	0.399
106	0.303	0.075	0.378
107	0.291	0.070	0.345
108	0.314	0.081	0.404
109	0.315	0.074	0.368
110	0.307	0.075	0.365
111	0.307	0.076	0.379
112	0.302	0.086	0.371
113	0.295	0.082	0.315
201	0.336	0.077	0.531
202	0.331	0.084	0.544
203	0.327	0.068	0.392
204	0.323	0.073	0.431
205	0.293	0.065	0.491
206	0.308	0.082	0.371
207	0.322	0.058	0.405
208	0.296	0.078	0.401
209	0.298	0.080	0.363
210	0.274	0.085	0.353
211	0.272	0.093	0.368
212	0.264	0.096	0.324
213	0.291	0.085	0.402
301	0.322	0.071	0.423
302	0.324	0.076	0.499
303	0.259	0.085	0.396
304	0.331	0.067	0.416
305	0.328	0.061	0.411
306	0.313	0.085	0.395
307	0.298	0.085	0.395
308	0.303	0.077	0.450
309	0.297	0.077	0.383

310	0.309	0.078	0.386
311	0.298	0.082	0.394
312	0.275	0.095	0.384
313	0.286	0.092	0.377
401	0.283	0.103	0.382
402	0.335	0.079	0.423
403	0.326	0.076	0.373
404	0.327	0.087	0.432
405	0.306	0.066	0.379
406	0.273	0.070	0.318
407	0.300	0.084	0.338
408	0.296	0.089	0.340
409	0.302	0.082	0.336
410	0.294	0.080	0.322
411	0.274	0.079	0.329
412	0.304	0.105	0.347
413	0.294	0.096	0.379

Table A.27 Soybean grain yield and nutrient analysis data from Ottawa in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
101	12.19	5.90	12.9	25.7	0.624
102	12.19	6.08	12.9	25.7	0.580
103	12.19	5.22	12.9	25.6	0.562
104	12.19	5.04	12.9	25.7	0.560
105	12.19	5.13	13.0	25.6	0.524
106	12.19	4.90	12.9	25.7	0.505
107	12.19	5.77	12.9	25.7	0.493
108	12.19	5.99	12.8	25.8	0.538
109	12.19	5.58	12.9	25.6	0.513
110	12.19	5.63	12.7	25.6	0.496
111	12.19	6.36	12.7	25.7	0.525
112	12.19	5.95	12.7	25.5	0.522
113	12.19	5.36	12.7	25.4	0.504
201	11.19	5.81	12.8	25.8	0.611
202	11.19	5.86	12.8	25.6	0.604
203	11.19	5.54	12.8	25.7	0.563
204	11.19	5.18	12.8	25.7	0.557
205	11.19	4.72	12.9	25.5	0.481
206	11.19	5.54	12.9	25.7	0.458
207	11.19	5.58	12.9	25.5	0.547
208	11.19	5.63	12.7	25.7	0.536
209	11.19	5.68	12.7	25.7	0.518
210	11.19	5.36	12.6	25.5	0.495
211	11.19	5.99	12.7	25.5	0.529
212	11.19	5.49	12.7	25.6	0.476
213	11.19	5.72	12.7	25.2	0.508
301	12.19	6.49	12.8	25.7	0.577
302	12.19	7.04	13.0	25.8	0.618
303	12.19	5.45	13.0	25.5	0.508
304	12.19	4.63	12.9	25.5	0.585
305	12.19	4.95	12.9	25.9	0.551
306	12.19	5.81	12.8	25.8	0.580
307	12.19	5.81	12.7	25.5	0.465
308	12.19	5.99	12.7	25.7	0.475
309	12.19	5.72	12.8	25.8	0.538
310	12.19	5.68	12.6	25.7	0.472

311	12.19	6.27	12.6	25.7	0.582
312	12.19	6.04	12.6	25.5	0.508
313	12.19	5.99	12.5	25.4	0.521
401	12.19	6.49	12.9	25.7	0.594
402	12.19	6.86	12.8	25.6	0.519
403	12.19	5.58	12.9	25.6	0.536
404	12.19	5.36	12.9	25.6	0.589
405	12.19	4.90	13.0	25.7	0.498
406	12.19	5.95	13.0	25.5	0.443
407	12.19	6.31	12.7	25.9	0.528
408	12.19	5.68	12.7	25.9	0.480
409	12.19	5.86	12.8	25.7	0.464
410	12.19	6.22	12.7	26.0	0.456
411	12.19	6.13	12.7	25.9	0.411
412	12.19	6.49	12.6	25.7	0.484
413	12.19	6.49	12.5	25.6	0.463

Table A.28 Initial soil sample data from Ottawa.

Plots	Depth (m)	pH	Buffer pH	P (ppm)	K (ppm)	SO_4^{2+} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	OM (%)	Cl^- (ppm)
101-113	0-0.08	5.6	6.3	10	156	4.0	17.2	4.8	3.1	4.4
101-113	0.08-0.15	5.7	6.1	7	156	3.4	9.3	4.0	2.8	3.0
101-113	0.15-0.23	6.0	6.4	5	208	3.0	8.1	2.3	2.3	2.7
101-113	0.23-0.31	6.0	6.4	5	250	2.7	7.7	1.5	2.1	1.7
101-113	0.31-0.61	6.6	-	5	297	5.2	6.5	0.9	1.4	0.6
101-113	0.61-0.91	6.9	-	4	303	7.9	6.0	0.7	1.2	1.8
114-127	0-0.08	5.7	6.5	7	151	3.3	13.4	5.0	2.9	1.2
114-127	0.08-0.15	5.8	6.4	5	149	2.1	7.5	4.2	2.6	0.1
114-127	0.15-0.23	6.0	6.5	4	184	1.4	6.8	2.9	2.5	0.7
114-127	0.23-0.31	6.0	6.4	4	230	2.0	6.7	2.1	2.2	0.3
114-127	0.31-0.61	6.4	6.7	4	316	6.7	5.3	1.2	1.5	1.8
114-127	0.61-0.91	7.0	-	4	300	9.1	3.8	0.7	1.3	2.8
201-213	0-0.08	5.8	6.5	12	171	5.5	13.4	3.7	3.0	4.0
201-213	0.08-0.15	5.8	6.3	6	168	3.2	7.7	3.8	2.8	3.5
201-213	0.15-0.23	5.9	6.5	5	190	2.5	5.3	2.0	2.4	2.5
201-213	0.23-0.31	5.9	6.4	5	250	2.9	6.0	1.4	2.4	2.6
201-213	0.31-0.61	6.2	6.7	8	327	6.5	5.3	0.9	1.7	2.7
201-213	0.61-0.91	6.7	-	5	326	9.5	3.9	0.6	1.2	4.5
214-227	0-0.08	5.7	6.5	11	147	5.2	11.2	6.3	2.9	1.4
214-227	0.08-0.15	6.0	6.4	5	165	3.9	5.1	4.7	2.6	1.2
214-227	0.15-0.23	6.0	6.5	5	193	3.8	5.1	3.2	2.4	1.8
214-227	0.23-0.31	6.1	6.5	5	254	3.6	5.9	1.8	2.3	1.4
214-227	0.31-0.61	6.2	6.6	4	321	5.3	5.4	1.1	1.4	0.8
214-227	0.61-0.91	6.6	-	4	323	7.7	5.6	0.7	1.0	2.5
301-313	0-0.08	5.6	6.4	13	147	5.7	14.5	4.1	3.2	4.6
301-313	0.08-0.15	5.9	6.4	6	147	3.5	7.3	3.5	2.8	2.6
301-313	0.15-0.23	6.1	6.6	5	194	2.5	6.4	1.3	2.6	1.8
301-313	0.23-0.31	6.3	6.6	5	261	4.1	5.0	0.8	2.0	1.1
301-313	0.31-0.61	6.4	6.8	4	320	6.9	6.2	0.6	1.3	1.0
301-313	0.61-0.91	7.0	-	4	297	9.7	4.9	0.5	0.8	1.4
314-327	0-0.08	5.6	6.5	7	138	4.6	12.8	7.5	2.8	1.3
314-327	0.08-0.15	5.9	6.6	5	159	2.2	6.9	4.8	2.7	0.8
314-327	0.15-0.23	6.0	6.6	5	177	2.5	7.3	3.6	2.2	0.3
314-327	0.23-0.31	6.3	6.6	5	236	2.6	4.6	1.8	2.0	0.7
314-327	0.31-0.61	6.4	6.8	4	265	5.9	5.7	1.3	1.6	1.2
314-327	0.61-0.91	6.9	-	3	277	8.7	4.4	0.7	0.9	4.0
401-413	0-0.08	5.8	6.5	8	154	6.7	12.2	3.4	3.2	4.6
401-413	0.08-0.15	6.0	6.4	6	156	5.5	8.3	2.6	2.8	4.4
401-413	0.15-0.23	6.0	6.6	4	175	2.7	6.3	2.6	2.4	2.7
401-413	0.23-0.31	6.1	6.6	5	241	3.0	5.9	1.9	1.9	1.2
401-413	0.31-0.61	6.3	6.8	4	294	5.3	6.0	0.7	1.5	2.1
401-413	0.61-0.91	6.7	-	4	271	8.0	5.2	0.5	1.2	2.4
414-427	0-0.08	5.8	6.6	8	144	4.2	12.1	7.2	3.0	1.9
414-427	0.08-0.15	5.9	6.5	6	141	2.8	8.3	4.3	2.5	0.8
414-427	0.15-0.23	6.0	6.5	5	205	4.6	6.2	1.5	2.2	3.2
414-427	0.23-0.31	6.2	6.6	4	269	3.6	5.7	0.6	2.2	2.5
414-427	0.31-0.61	6.5	-	3	324	6.8	6.1	1.0	1.4	4.1
414-427	0.61-0.91	6.8	-	4	308	9.4	5.6	0.9	1.2	5.7

Table A.29 Soil sample data from Ottawa collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

Plot	Depth (m)	Location	P (ppm)
102	0-0.08	Row	41
102	0.08-0.15	Row	55
102	0.15-0.23	Row	5
102	0.23-0.31	Row	3
102	0.31-0.61	Row	3
102	0-0.08	Row Middle	14
102	0.08-0.15	Row Middle	5
102	0.15-0.23	Row Middle	3
102	0.23-0.31	Row Middle	3
102	0.31-0.61	Row Middle	2
104	0-0.08	Row	16
104	0.08-0.15	Row	6
104	0.15-0.23	Row	3
104	0.23-0.31	Row	3
104	0.31-0.61	Row	2
104	0-0.08	Row Middle	16
104	0.08-0.15	Row Middle	5
104	0.15-0.23	Row Middle	3
104	0.23-0.31	Row Middle	2
104	0.31-0.61	Row Middle	2
108	0-0.08	Row	20
108	0.08-0.15	Row	5
108	0.15-0.23	Row	4
108	0.23-0.31	Row	3
108	0.31-0.61	Row	4
108	0-0.08	Row Middle	13
108	0.08-0.15	Row Middle	4
108	0.15-0.23	Row Middle	3
108	0.23-0.31	Row Middle	3
108	0.31-0.61	Row Middle	2
112	0-0.08	Row	17
112	0.08-0.15	Row	6
112	0.15-0.23	Row	4
112	0.23-0.31	Row	3

112	0.31-0.61	Row	2
112	0-0.08	Row Middle	9
112	0.08-0.15	Row Middle	5
112	0.15-0.23	Row Middle	3
112	0.23-0.31	Row Middle	2
112	0.31-0.61	Row Middle	3
113	0-0.08	Row	11
113	0.08-0.15	Row	7
113	0.15-0.23	Row	3
113	0.23-0.31	Row	3
113	0.31-0.61	Row	2
113	0-0.08	Row Middle	9
113	0.08-0.15	Row Middle	5
113	0.15-0.23	Row Middle	4
113	0.23-0.31	Row Middle	3
113	0.31-0.61	Row Middle	2
202	0-0.08	Row	43
202	0.08-0.15	Row	9
202	0.15-0.23	Row	5
202	0.23-0.31	Row	3
202	0.31-0.61	Row	3
202	0-0.08	Row Middle	6
202	0.08-0.15	Row Middle	4
202	0.15-0.23	Row Middle	12
202	0.23-0.31	Row Middle	6
202	0.31-0.61	Row Middle	3
205	0-0.08	Row	11
205	0.08-0.15	Row	6
205	0.15-0.23	Row	4
205	0.23-0.31	Row	2
205	0.31-0.61	Row	2
205	0-0.08	Row Middle	13
205	0.08-0.15	Row Middle	6
205	0.15-0.23	Row Middle	2
205	0.23-0.31	Row Middle	2
205	0.31-0.61	Row Middle	3
207	0-0.08	Row	13

207	0.08-0.15	Row	6
207	0.15-0.23	Row	3
207	0.23-0.31	Row	2
207	0.31-0.61	Row	2
207	0-0.08	Row Middle	10
207	0.08-0.15	Row Middle	6
207	0.15-0.23	Row Middle	3
207	0.23-0.31	Row Middle	2
207	0.31-0.61	Row Middle	2
210	0-0.08	Row	15
210	0.08-0.15	Row	11
210	0.15-0.23	Row	4
210	0.23-0.31	Row	2
210	0.31-0.61	Row	2
210	0-0.08	Row Middle	8
210	0.08-0.15	Row Middle	4
210	0.15-0.23	Row Middle	2
210	0.23-0.31	Row Middle	2
210	0.31-0.61	Row Middle	2
211	0-0.08	Row	24
211	0.08-0.15	Row	20
211	0.15-0.23	Row	6
211	0.23-0.31	Row	3
211	0.31-0.61	Row	2
211	0-0.08	Row Middle	7
211	0.08-0.15	Row Middle	4
211	0.15-0.23	Row Middle	3
211	0.23-0.31	Row Middle	4
211	0.31-0.61	Row Middle	2
302	0-0.08	Row	55
302	0.08-0.15	Row	25
302	0.15-0.23	Row	4
302	0.23-0.31	Row	6
302	0.31-0.61	Row	2
302	0-0.08	Row Middle	18
302	0.08-0.15	Row Middle	6
302	0.15-0.23	Row Middle	3

302	0.23-0.31	Row Middle	3
302	0.31-0.61	Row Middle	3
303	0-0.08	Row	14
303	0.08-0.15	Row	4
303	0.15-0.23	Row	3
303	0.23-0.31	Row	3
303	0.31-0.61	Row	2
303	0-0.08	Row Middle	16
303	0.08-0.15	Row Middle	5
303	0.15-0.23	Row Middle	3
303	0.23-0.31	Row Middle	3
303	0.31-0.61	Row Middle	2
304	0-0.08	Row	29
304	0.08-0.15	Row	76
304	0.15-0.23	Row	8
304	0.23-0.31	Row	4
304	0.31-0.61	Row	9
304	0-0.08	Row Middle	17
304	0.08-0.15	Row Middle	22
304	0.15-0.23	Row Middle	4
304	0.23-0.31	Row Middle	3
304	0.31-0.61	Row Middle	3
308	0-0.08	Row	11
308	0.08-0.15	Row	13
308	0.15-0.23	Row	4
308	0.23-0.31	Row	2
308	0.31-0.61	Row	2
308	0-0.08	Row Middle	7
308	0.08-0.15	Row Middle	3
308	0.15-0.23	Row Middle	2
308	0.23-0.31	Row Middle	2
308	0.31-0.61	Row Middle	2
311	0-0.08	Row	23
311	0.08-0.15	Row	17
311	0.15-0.23	Row	3
311	0.23-0.31	Row	3
311	0.31-0.61	Row	3

311	0-0.08	Row Middle	18
311	0.08-0.15	Row Middle	7
311	0.15-0.23	Row Middle	3
311	0.23-0.31	Row Middle	3
311	0.31-0.61	Row Middle	2
401	0-0.08	Row	27
401	0.08-0.15	Row	8
401	0.15-0.23	Row	5
401	0.23-0.31	Row	4
401	0.31-0.61	Row	3
401	0-0.08	Row Middle	15
401	0.08-0.15	Row Middle	7
401	0.15-0.23	Row Middle	6
401	0.23-0.31	Row Middle	4
401	0.31-0.61	Row Middle	4
405	0-0.08	Row	9
405	0.08-0.15	Row	4
405	0.15-0.23	Row	3
405	0.23-0.31	Row	2
405	0.31-0.61	Row	2
405	0-0.08	Row Middle	8
405	0.08-0.15	Row Middle	5
405	0.15-0.23	Row Middle	3
405	0.23-0.31	Row Middle	3
405	0.31-0.61	Row Middle	2
407	0-0.08	Row	22
407	0.08-0.15	Row	24
407	0.15-0.23	Row	4
407	0.23-0.31	Row	3
407	0.31-0.61	Row	2
407	0-0.08	Row Middle	7
407	0.08-0.15	Row Middle	10
407	0.15-0.23	Row Middle	3
407	0.23-0.31	Row Middle	2
407	0.31-0.61	Row Middle	2
412	0-0.08	Row	13
412	0.08-0.15	Row	7

412	0.15-0.23	Row	3
412	0.23-0.31	Row	4
412	0.31-0.61	Row	2
412	0-0.08	Row Middle	8
412	0.08-0.15	Row Middle	4
412	0.15-0.23	Row Middle	3
412	0.23-0.31	Row Middle	2
412	0.31-0.61	Row Middle	2
413	0-0.08	Row	19
413	0.08-0.15	Row	39
413	0.15-0.23	Row	3
413	0.23-0.31	Row	3
413	0.31-0.61	Row	2
413	0-0.08	Row Middle	11
413	0.08-0.15	Row Middle	5
413	0.15-0.23	Row Middle	3
413	0.23-0.31	Row Middle	3
413	0.31-0.61	Row Middle	2

Table A.30 Additional plot soil sample data and re-sampled plots from Ottawa collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

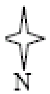
Plot	Depth (m)	Location	P (ppm)
102	0-0.08	Row	19
102	0.08-0.15	Row	66
104	0-0.08	Row	16
104	0.08-0.15	Row	4
104	0-0.08	Row Middle	11
104	0.08-0.15	Row Middle	5
105	0-0.08	Row	11
105	0.08-0.15	Row	4
105	0.15-0.23	Row	3
105	0-0.08	Row Middle	9
105	0.08-0.15	Row Middle	4
105	0.15-0.23	Row Middle	3
112	0-0.08	Row	7
112	0.08-0.15	Row	3
202	0-0.08	Row	12
202	0.08-0.15	Row	3
209	0-0.08	Row	8
209	0.08-0.15	Row	4
209	0.15-0.23	Row	3
209	0-0.08	Row Middle	8
209	0.08-0.15	Row Middle	3
209	0.15-0.23	Row Middle	3
211	0-0.08	Row	18
211	0.08-0.15	Row	11
302	0-0.08	Row	23
302	0.08-0.15	Row	8
302	0-0.08	Row Middle	20
302	0.08-0.15	Row Middle	7
304	0-0.08	Row	33
304	0.08-0.15	Row	77
311	0-0.08	Row Middle	10
311	0.08-0.15	Row Middle	4
312	0-0.08	Row	6
312	0.08-0.15	Row	3

312	0.15-0.23	Row	3
312	0-0.08	Row Middle	6
312	0.08-0.15	Row Middle	3
312	0.15-0.23	Row Middle	3
401	0-0.08	Row	11
401	0.08-0.15	Row	5
407	0-0.08	Row	11
407	0.08-0.15	Row	6
409	0-0.08	Row	6
409	0.08-0.15	Row	3
409	0.15-0.23	Row	3
409	0-0.08	Row Middle	8
409	0.08-0.15	Row Middle	4
409	0.15-0.23	Row Middle	3
412	0-0.08	Row	10
412	0.08-0.15	Row	6
413	0-0.08	Row	9
413	0.08-0.15	Row	13

Manhattan – Agronomy North Farm

P Management in Reduced Tillage (Manhattan, KS)

Plot length = 80 ft, Alley = 30 ft



Trt.	Starter P	Broadcast P	Deep Band P	Total P	Starter P	Broadcast P	Deep Band P	Total P	Broadcast P	Total P
	Wheat				Sorghum				Soybeans	
1	0	0	0	0	0	0	0	0	0	0
2	20	0	0	20	20	0	0	20	0	0
3	0	40	0	40	0	40	0	40	0	0
4	20	20	0	40	20	20	0	40	0	0
5	0	0	40	40	0	0	40	40	0	0
6	20	0	20	40	20	0	20	40	0	0
7	0	80	0	80	0	80	0	80	0	0
8	20	60	0	80	20	60	0	80	0	0
9	0	0	80	80	0	0	80	80	0	0
10	20	0	60	80	20	0	60	80	0	0
11	20	60	0	80	20	60	0	80	40	40
12	20	0	60	80	20	0	60	80	40	40

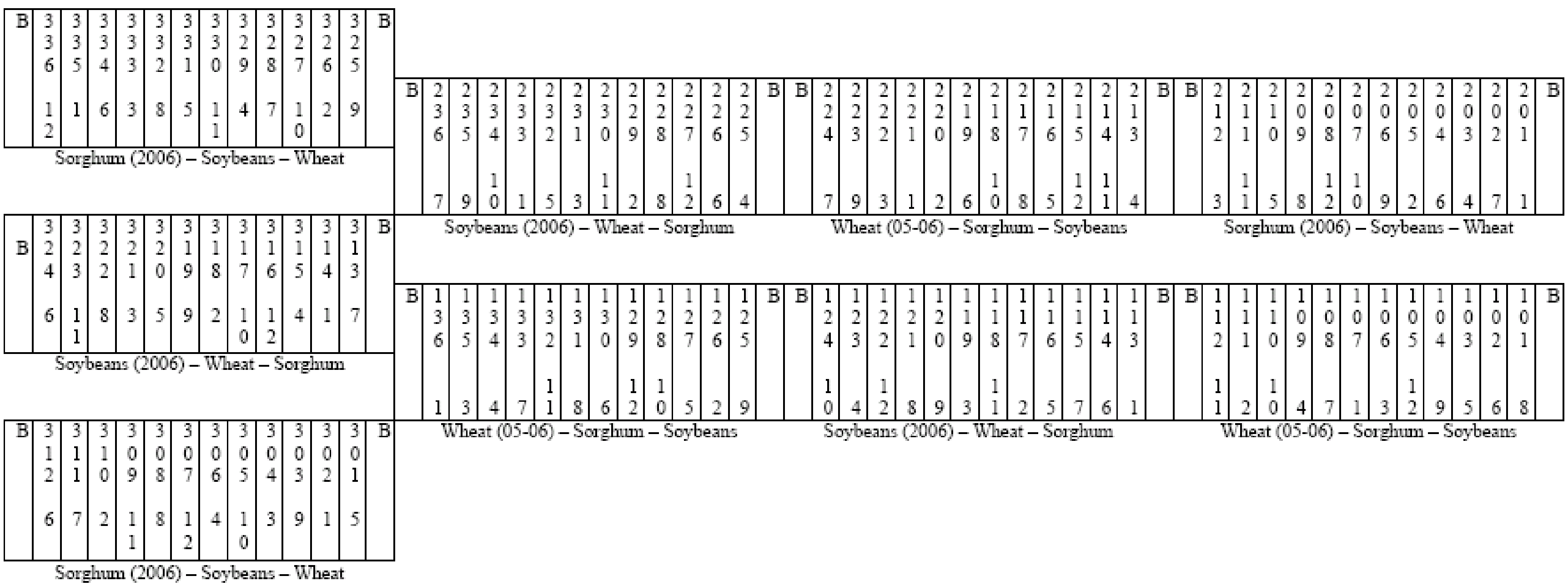


Table A.31 Wheat tissue nutrient analysis and biomass yield data from Manhattan in the 2005-06 growing season.

Plot	-------------------Flag Leaf-------------------			-------------------Whole Plant (mid bloom)-------------------			
	N	P	K	N	P	K	Biomass
	(%)	(%)	(%)	(%)	(%)	(%)	(kg 3.1m^{-2})
101	3.64	0.23	0.91	0.76	0.06	1.01	2.95
102	3.72	0.23	1.01	1.04	0.08	1.13	2.77
103	3.75	0.24	0.94	0.96	0.07	1.21	3.48
104	3.87	0.24	0.97	1.06	0.08	1.40	2.96
105	3.77	0.25	0.92	1.17	0.10	1.42	4.46
106	4.12	0.27	0.98	1.24	0.10	1.41	3.40
107	3.88	0.25	0.92	1.09	0.08	1.30	3.53
108	3.63	0.24	0.93	1.05	0.08	1.41	3.50
109	3.76	0.23	0.90	1.08	0.08	1.20	3.28
110	3.83	0.23	0.94	1.07	0.06	1.51	2.77
111	3.76	0.23	0.96	0.97	0.07	1.25	3.12
112	3.65	0.23	0.89	0.95	0.07	1.48	3.18
125	3.87	0.24	0.93	0.97	0.08	1.13	2.73
126	3.90	0.24	0.95	0.95	0.08	1.40	3.83
127	3.88	0.24	0.93	0.97	0.08	1.26	4.20
128	3.85	0.24	0.92	1.01	0.09	1.28	2.66
129	3.88	0.25	0.99	0.89	0.08	1.37	2.74
130	3.73	0.24	0.99	0.98	0.07	1.31	2.42
131	3.59	0.24	0.91	0.84	0.08	1.18	3.12
132	3.60	0.24	1.03	0.85	0.10	1.51	3.61
133	3.69	0.26	1.02	0.91	0.09	1.37	3.26
134	3.93	0.26	1.00	1.03	0.09	1.63	6.99
135	3.81	0.27	0.97	0.80	0.08	1.49	3.09
136	3.72	0.25	0.95	0.77	0.06	1.13	3.24
213	3.64	0.25	0.97	0.89	0.06	1.27	3.42
214	3.89	0.28	1.02	0.87	0.06	1.36	3.43
215	3.27	0.24	0.95	0.93	0.09	1.34	3.38
216	3.61	0.26	1.04	0.90	0.08	1.18	3.41
217	3.62	0.26	0.96	0.90	0.09	1.33	3.94
218	3.70	0.25	1.01	0.91	0.09	1.10	3.96
219	3.63	0.26	1.07	0.84	0.06	1.23	3.33
220	3.80	0.25	0.99	1.05	0.07	1.40	1.96
221	3.66	0.26	0.89	0.94	0.07	1.28	3.61
222	3.46	0.27	0.99	0.87	0.07	1.12	1.74
223	3.58	0.25	0.89	1.08	0.08	1.04	2.93

224	3.83	0.28	0.97	0.81	0.07	1.15	2.84

Table A.32 Wheat grain yield and nutrient analysis data from Manhattan in the 2005-06 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	----------------------Grain----------------------		
					N (%)	P (%)	K (%)
101	19.8	14.65	11.5	26.58	2.53	0.35	0.39
102	19.8	14.83	11.5	26.89	2.74	0.33	0.36
103	19.8	15.65	11.6	26.89	2.70	0.32	0.32
104	19.8	13.92	11.6	26.85	2.66	0.32	0.33
105	19.8	14.78	11.7	26.80	2.49	0.35	0.36
106	19.8	14.92	11.5	26.58	2.47	0.33	0.34
107	19.8	14.69	11.6	26.76	2.46	0.35	0.37
108	19.8	15.01	11.5	26.44	2.48	0.36	0.36
109	19.8	13.56	11.6	26.89	2.60	0.36	0.34
110	19.8	14.10	11.7	26.94	2.54	0.34	0.33
111	19.8	15.01	11.5	27.07	2.49	0.42	0.40
112	19.8	14.74	11.7	26.85	2.57	0.37	0.35
125	19.8	13.33	11.6	26.44	2.61	0.39	0.36
126	19.8	13.06	11.7	26.39	2.75	0.38	0.34
127	19.8	13.38	11.5	26.48	2.49	0.37	0.33
128	19.8	13.29	11.7	26.30	2.53	0.32	0.28
129	19.8	13.83	11.6	26.48	2.34	0.42	0.37
130	19.8	13.38	11.6	26.30	2.58	0.34	0.30
131	19.8	12.61	11.7	26.44	2.35	0.36	0.32
132	19.8	13.20	11.5	26.26	2.46	0.39	0.36
133	19.8	12.47	11.5	26.62	2.35	0.38	0.34
134	19.8	11.61	11.8	26.58	2.57	0.34	0.32
135	19.8	12.24	11.6	26.53	2.29	0.49	0.45
136	19.8	13.92	11.4	26.21	2.40	0.36	0.33
213	19.8	14.60	11.3	26.62	2.35	0.40	0.35
214	19.8	14.78	11.5	26.71	2.28	0.43	0.39
215	19.8	15.33	11.5	26.53	2.21	0.38	0.36
216	19.8	14.78	11.6	26.76	2.21	0.43	0.39
217	19.8	14.60	11.5	26.48	2.15	0.38	0.35
218	19.8	14.19	11.5	26.76	2.22	0.37	0.32
219	19.8	14.92	11.6	26.35	2.42	0.44	0.39
220	19.8	14.47	11.5	26.35	2.52	0.42	0.37
221	19.8	15.01	11.6	26.62	2.28	0.44	0.40
222	19.8	16.28	11.4	26.62	2.17	0.44	0.38
223	19.8	15.42	11.6	26.67	2.36	0.44	0.42

224	19.8	15.28	11.5	26.48	2.35	0.49	0.44

Table A.33 Grain sorghum tissue nutrient analysis and biomass yield data from Manhattan in the 2006 growing season.

Plot	--------------------Flag Leaf-----------------			-------------------Whole Plant (mid bloom)-------------------			
	N	P	K	N	P	K	Biomass
	(%)	(%)	(%)	(%)	(%)	(%)	(kg $4.0m^{-2}$)
201	2.43	0.28	1.54	0.69	0.11	1.86	6.77
202	2.64	0.30	1.59	0.91	0.15	1.96	6.53
203	2.53	0.30	1.55	0.75	0.13	1.94	7.09
204	2.64	0.31	1.68	0.80	0.13	1.94	6.53
205	2.79	0.32	1.52	0.83	0.11	2.00	6.53
206	2.59	0.30	1.63	0.71	0.11	1.97	6.03
207	2.55	0.30	1.66	0.60	0.11	2.16	5.85
208	2.67	0.32	1.67	0.74	0.13	2.34	6.36
209	2.69	0.30	1.59	0.69	0.13	2.38	6.60
210	2.86	0.32	1.55	0.71	0.15	2.62	6.01
211	2.78	0.30	1.58	0.54	0.12	2.04	6.77
212	2.73	0.30	1.63	0.51	0.11	1.87	6.72
301	2.46	0.26	1.41	0.55	0.11	1.89	6.45
302	2.70	0.25	1.29	0.78	0.11	2.29	6.32
303	2.63	0.25	1.45	0.72	0.10	2.08	6.56
304	3.04	0.28	1.31	0.95	0.12	2.05	6.81
305	2.67	0.27	1.36	0.49	0.10	2.24	6.63
306	2.90	0.29	1.36	0.79	0.12	1.90	6.83
307	2.96	0.29	1.37	0.83	0.14	2.10	7.36
308	2.79	0.28	1.43	0.71	0.12	2.40	5.80
309	3.03	0.29	1.38	0.73	0.11	2.35	6.54
310	3.05	0.28	1.33	0.78	0.13	2.21	6.95
311	2.97	0.27	1.31	0.81	0.13	2.36	6.67
312	2.99	0.25	1.28	0.97	0.12	2.35	7.25
325	2.59	0.24	1.37	0.64	0.09	2.02	6.10
326	2.51	0.24	1.49	0.47	0.07	2.18	6.41
327	2.74	0.26	1.38	0.67	0.12	2.14	5.64
328	2.51	0.24	1.42	0.49	0.08	2.15	5.68
329	2.81	0.25	1.31	0.50	0.08	2.08	5.66
330	2.80	0.24	1.35	0.47	0.07	2.20	5.74
331	2.73	0.23	1.25	0.52	0.09	2.19	5.57
332	2.82	0.25	1.33	0.57	0.11	2.05	6.36
333	2.87	0.24	1.39	0.61	0.10	2.14	6.07
334	2.70	0.24	1.43	0.62	0.09	2.21	6.45
335	2.87	0.23	1.27	0.60	0.09	1.97	5.70

336	2.89	0.26	1.22	0.62	0.11	2.15	6.17

Table A.34 Grain sorghum grain yield and nutrient analysis data from Manhattan in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	----Grain---- N (%)	P (%)	K (%)
201	5.3	5.17	1.52	0.29	0.27
202	5.3	6.21	1.61	0.29	0.24
203	5.3	6.21	1.52	0.33	0.28
204	5.3	5.85	1.50	0.30	0.25
205	5.3	5.71	1.62	0.31	0.25
206	5.3	5.49	1.53	0.30	0.26
207	5.3	5.90	1.46	0.35	0.29
208	5.3	6.03	1.56	0.29	0.24
209	5.3	6.08	1.46	0.33	0.26
210	5.3	5.53	1.58	0.34	0.27
211	5.3	5.35	1.55	0.33	0.26
212	5.3	4.94	1.62	0.31	0.23
301	5.3	5.71	1.39	0.28	0.21
302	5.3	5.90	1.54	0.26	0.24
303	5.3	5.76	1.49	0.25	0.22
304	5.3	5.94	1.55	0.27	0.21
305	5.3	5.90	1.31	0.26	0.20
306	5.3	5.94	1.43	0.30	0.25
307	5.3	6.12	1.57	0.30	0.26
308	5.3	6.26	1.48	0.29	0.26
309	5.3	6.12	1.48	0.31	0.26
310	5.3	6.12	1.51	0.29	0.23
311	5.3	6.26	1.56	0.29	0.24
312	5.3	5.90	1.66	0.26	0.22
325	5.3	5.31	1.41	0.26	0.23
326	5.3	5.99	1.45	0.24	0.23
327	5.3	5.58	1.35	0.27	0.23
328	5.3	5.58	1.33	0.26	0.23
329	5.3	5.31	1.39	0.23	0.22
330	5.3	5.26	1.49	0.24	0.22
331	5.3	5.08	1.49	0.24	0.22
332	5.3	5.71	1.51	0.26	0.24
333	5.3	5.22	1.57	0.25	0.22
334	5.3	5.26	1.53	0.22	0.20
335	5.3	5.26	1.58	0.26	0.23

336	5.3	5.67	1.57	0.29	0.25

Table A.35 Soybean grain yield and nutrient analysis data from Manhattan in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	----------------------Grain----------------------		
					N (%)	P (%)	K (%)
113	24.4	12.15	10.2	25.40	6.17	0.692	1.92
114	24.4	11.70	11.3	24.99	6.29	0.707	1.98
115	24.4	11.79	9.90	24.53	6.28	0.698	1.87
116	24.4	11.75	9.90	24.63	6.24	0.692	1.91
117	24.4	11.70	10.6	24.99	6.10	0.694	1.90
118	24.4	10.75	10.1	24.67	6.27	0.717	1.98
119	24.4	11.07	10.1	25.08	6.10	0.728	2.03
120	24.4	11.43	9.70	25.26	6.34	0.718	1.98
121	24.4	11.38	9.80	23.13	6.28	0.692	1.95
122	24.4	11.38	10.1	24.49	6.32	0.736	1.94
123	24.4	11.75	10.2	24.90	6.06	0.691	1.94
124	24.4	11.29	9.70	24.94	6.12	0.683	1.91
225	24.4	12.02	9.80	24.44	5.86	0.721	2.02
226	24.4	11.29	10.4	25.31	5.99	0.689	1.96
227	24.4	11.47	10.6	25.76	6.15	0.691	1.99
228	24.4	12.24	10.6	24.49	6.19	0.682	1.93
229	24.4	10.79	10.2	24.40	6.14	0.634	1.97
230	24.4	11.70	10.0	25.67	6.08	0.706	2.00
231	24.4	11.97	10.6	25.12	6.08	0.627	1.98
232	24.4	11.70	10.1	25.26	6.18	0.621	1.92
233	24.4	12.02	9.90	24.35	6.38	0.631	1.94
234	24.4	11.84	9.40	24.17	6.32	0.643	1.91
235	24.4	11.70	9.70	25.26	6.03	0.616	1.95
236	24.4	11.84	10.4	24.53	6.17	0.624	1.92
313	24.4	11.20	9.60	23.85	6.14	0.691	1.97
314	24.4	12.70	10.2	23.40	6.15	0.638	1.96
315	24.4	11.02	9.70	25.08	5.91	0.680	1.92
316	24.4	11.93	10.2	24.67	6.06	0.725	2.00
317	24.4	10.97	10.1	25.44	6.00	0.65	1.96
318	24.4	12.15	10.3	24.76	5.88	0.647	1.93
319	24.4	11.65	10.1	23.31	5.94	0.638	1.91
320	24.4	10.97	10.1	25.35	6.07	0.623	1.85
321	24.4	11.65	10.0	25.21	6.16	0.632	1.83
322	24.4	11.07	10.2	25.44	5.97	0.701	1.93
323	24.4	12.24	10.5	25.21	6.01	0.729	1.96

324	24.4	11.88	9.80	25.44	6.00	0.638	1.91

Table A.36 Wheat tissue nutrient analysis and biomass yield data from Manhattan in the 2006-07 growing season.

Plot	--------------Flag Leaf--------------			---------------------Whole Plant---------------------			
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)	Biomass (kg $0.35m^{-2}$)
113	3.73	0.314	1.73	0.91	0.158	1.17	0.185
114	3.33	0.310	1.59	0.97	0.218	1.08	0.243
115	3.16	0.270	1.54	1.11	0.223	1.23	0.220
116	3.28	0.291	1.54	1.06	0.219	1.19	0.234
117	3.50	0.342	1.73	1.13	0.163	1.44	0.184
118	3.29	0.316	1.58	1.18	0.254	1.05	0.198
119	3.17	0.284	1.39	1.05	0.204	1.35	0.170
120	3.35	0.299	1.57	0.98	0.207	1.21	0.193
121	3.45	0.306	1.69	1.24	0.235	1.28	0.164
122	3.28	0.321	1.54	1.06	0.223	1.32	0.204
123	3.23	0.292	1.67	0.95	0.154	1.39	0.201
124	3.18	0.296	1.71	0.76	0.142	1.10	0.151
225	3.13	0.310	1.70	0.86	0.208	1.16	0.202
226	2.89	0.271	1.44	1.04	0.208	1.06	0.255
227	2.99	0.287	1.54	1.07	0.229	1.21	0.147
228	2.99	0.284	1.52	1.14	0.271	1.12	0.200
229	3.25	0.226	1.57	1.06	0.171	1.04	0.173
230	3.20	0.303	1.58	1.07	0.242	0.99	0.201
231	3.45	0.267	1.64	1.09	0.175	1.23	0.191
232	3.38	0.275	1.48	1.05	0.179	0.99	0.211
233	3.68	0.249	1.63	1.17	0.172	1.18	0.190
234	3.02	0.276	1.44	0.93	0.20	0.92	0.213
235	3.21	0.247	1.28	1.12	0.221	1.28	0.200
236	3.25	0.264	1.33	0.96	0.223	1.19	0.202
313	3.31	0.279	1.36	1.09	0.199	1.27	0.217
314	3.55	0.248	1.47	1.19	0.135	1.07	0.180
315	3.16	0.298	1.45	0.99	0.210	1.28	0.153
316	2.73	0.255	1.27	0.92	0.240	1.07	0.155
317	2.64	0.244	1.24	1.09	0.267	0.83	0.145
318	3.15	0.252	1.40	0.97	0.196	0.94	0.249
319	3.25	0.303	1.49	1.05	0.261	1.04	0.163
320	3.15	0.260	1.40	1.09	0.203	0.99	0.301
321	3.07	0.263	1.51	1.06	0.184	1.04	0.183
322	2.82	0.272	1.42	1.04	0.217	1.36	0.220
323	2.97	0.286	1.43	1.03	0.197	1.17	0.255

324	2.78	0.239	1.37	1.14	0.232	1.38	0.240

Table A.37 Wheat grain yield and nutrient analysis data from Manhattan in the 2006-07 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	---Grain---		
					N (%)	P (%)	K (%)
113	24.4	9.34	12.2	25.08	3.73	0.31	1.73
114	24.4	9.98	12.0	25.17	3.33	0.31	1.59
115	24.4	10.20	11.5	25.12	3.16	0.27	1.54
116	24.4	10.29	11.3	24.99	3.28	0.29	1.54
117	24.4	10.29	11.4	24.58	3.50	0.34	1.73
118	24.4	10.20	11.5	25.17	3.29	0.32	1.58
119	24.4	10.61	11.5	25.08	3.17	0.28	1.39
120	24.4	10.39	11.4	25.08	3.36	0.30	1.57
121	24.4	10.48	11.6	25.17	3.45	0.31	1.69
122	24.4	9.89	11.3	25.35	3.28	0.32	1.54
123	24.4	10.25	11.8	25.44	3.23	0.29	1.67
124	24.4	9.52	12.1	24.58	3.18	0.30	1.71
225	24.4	9.70	11.8	25.12	3.13	0.31	1.70
226	24.4	10.84	13.1	24.58	2.89	0.27	1.44
227	24.4	9.98	11.8	24.99	2.99	0.29	1.54
228	24.4	10.70	12.1	24.81	2.99	0.28	1.53
229	24.4	9.16	12.2	24.63	3.25	0.23	1.57
230	24.4	10.39	11.4	25.03	3.20	0.30	1.58
231	24.4	9.70	12.1	24.58	3.45	0.27	1.64
232	24.4	10.61	11.6	24.94	3.38	0.28	1.48
233	24.4	8.71	11.8	24.31	3.68	0.25	1.63
234	24.4	9.98	11.6	25.31	3.02	0.28	1.44
235	24.4	10.11	11.5	24.40	3.21	0.25	1.28
236	24.4	10.70	11.5	25.08	3.25	0.26	1.33
313	24.4	10.57	11.5	25.26	3.31	0.28	1.36
314	24.4	9.34	11.7	25.12	3.55	0.25	1.47
315	24.4	11.20	11.4	25.31	3.16	0.30	1.45
316	24.4	9.84	11.4	25.12	2.73	0.26	1.27
317	24.4	9.25	11.9	25.62	2.64	0.24	1.24
318	24.4	9.93	11.5	24.99	3.15	0.25	1.40
319	24.4	10.43	11.6	25.21	3.25	0.30	1.49
320	24.4	8.80	11.9	24.81	3.15	0.26	1.40
321	24.4	10.20	11.5	25.12	3.07	0.26	1.51
322	24.4	10.34	11.6	25.26	2.82	0.27	1.42
323	24.4	10.16	11.4	24.99	2.97	0.29	1.43

324	24.4	10.52	11.5	25.44	2.78	0.24	1.37

Table A.38 Grain sorghum tissue nutrient analysis and biomass yield data from Manhattan in the 2007 growing season.

Plot	--------------Flag Leaf--------------			---------------------Stover (GS 2)---------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	(kg 1.4m^{-2})
101	2.83	0.331	1.09	2.10	0.396	4.06	0.137
102	2.86	0.323	1.03	2.35	0.371	4.27	0.154
103	2.87	0.335	1.14	2.02	0.369	4.41	0.149
104	2.89	0.343	1.07	2.10	0.362	4.66	0.153
105	2.84	0.357	1.16	2.30	0.388	4.93	0.145
106	2.85	0.349	1.02	2.18	0.360	5.06	0.142
107	2.76	0.331	1.07	2.03	0.385	4.62	0.138
108	2.95	0.344	1.04	2.08	0.378	4.74	0.146
109	2.84	0.356	1.09	2.41	0.360	4.07	0.148
110	2.97	0.346	1.00	2.32	0.413	4.84	0.164
111	2.80	0.359	1.18	2.19	0.339	3.73	0.143
112	2.66	0.335	1.08	2.18	0.366	4.60	0.153
125	2.78	0.344	1.16	2.60	0.382	4.39	0.140
126	3.00	0.337	1.09	2.02	0.406	4.18	0.142
127	2.78	0.341	1.12	2.14	0.416	4.75	0.160
128	2.73	0.340	1.17	2.42	0.482	4.36	0.158
129	2.88	0.334	1.07	1.95	0.427	4.93	0.146
130	2.70	0.345	1.24	2.63	0.500	5.09	0.165
131	2.35	0.303	1.04	2.28	0.433	4.43	0.146
132	2.36	0.349	1.27	1.90	0.322	4.02	0.158
133	2.44	0.349	1.13	2.44	0.496	4.11	0.133
134	2.35	0.325	1.14	2.39	0.344	3.93	0.156
135	2.32	0.330	1.19	2.68	0.489	4.30	0.147
136	2.26	0.318	1.13	2.18	0.418	3.81	0.172
213	2.59	0.318	1.13	2.53	0.380	4.63	0.171
214	2.47	0.363	1.28	2.14	0.371	4.98	0.137
215	2.62	0.329	1.08	2.12	0.386	4.33	0.147
216	2.54	0.324	1.12	2.18	0.412	5.01	0.147
217	2.64	0.311	1.01	2.12	0.380	4.31	0.155
218	2.70	0.346	1.24	1.98	0.367	4.41	0.145
219	2.70	0.327	1.11	2.05	0.416	4.39	0.158
220	2.69	0.321	1.10	2.12	0.370	3.96	0.134
221	2.70	0.328	1.13	1.80	0.407	4.09	0.140
222	2.65	0.330	1.08	2.10	0.432	4.45	0.146
223	2.75	0.313	1.00	1.59	0.430	4.89	0.155

224	2.61	0.326	1.10	1.70	0.384	3.94	0.142

Table A.36 Continued.

Plot	--------Stover (mid bloom)--------			
	N	P	K	Dry Weight
	(%)	(%)	(%)	(kg $1.4m^{-2}$)
101	0.77	0.161	1.68	2.26
102	0.89	0.179	1.88	2.16
103	0.79	0.156	1.86	1.99
104	0.95	0.181	1.91	1.71
105	0.86	0.171	1.92	2.02
106	0.96	0.193	1.95	2.02
107	0.83	0.162	1.99	2.10
108	0.71	0.169	1.82	2.07
109	0.80	0.145	1.78	1.81
110	0.79	0.143	1.90	2.07
111	0.81	0.132	1.92	1.92
112	0.83	0.156	1.88	1.80
125	1.00	0.168	1.87	1.51
126	0.97	0.167	1.79	1.49
127	0.85	0.166	2.02	2.02
128	0.87	0.172	2.01	2.21
129	0.83	0.184	1.83	1.91
130	0.90	0.195	1.97	1.50
131	0.91	0.184	1.98	1.70
132	0.69	0.157	1.85	2.00
133	0.85	0.188	1.90	1.98
134	0.95	0.152	1.71	1.94
135	0.84	0.157	1.78	2.24
136	0.71	0.136	1.78	1.71
213	0.65	0.117	1.88	1.69
214	0.74	0.186	1.88	1.80
215	0.94	0.161	2.12	1.93
216	0.77	0.150	1.87	1.95
217	0.90	0.168	1.89	1.55
218	0.82	0.146	1.86	2.00
219	0.82	0.121	2.05	1.91
220	0.88	0.135	1.99	2.09
221	0.94	0.165	1.95	2.29
222	1.00	0.164	1.94	1.59
223	0.98	0.144	1.87	1.82
224	0.87	0.154	1.82	2.01

Table A.39 Grain sorghum grain yield and nutrient analysis data from Manhattan in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	----------------------Grain----------------------		
					N (%)	P (%)	K (%)
101	24.38	6.30	15.1	24.81	1.44	0.334	0.34
102	24.38	9.34	14.4	25.12	1.43	0.314	0.34
103	24.38	10.25	14.9	24.13	1.25	0.297	0.32
104	24.38	9.93	14.4	26.53	1.36	0.288	0.33
105	24.38	10.39	14.9	25.58	1.36	0.304	0.32
106	24.38	9.84	14.4	22.99	1.27	0.310	0.33
107	24.38	9.75	14.6	26.39	1.38	0.327	0.34
108	24.38	10.00	14.4	23.26	1.33	0.303	0.33
109	24.38	10.43	14.2	26.26	1.40	0.305	0.31
110	24.38	10.61	14.2	25.89	1.42	0.324	0.34
111	24.38	10.59	14.9	24.99	1.27	0.298	0.31
112	24.38	9.52	14.2	25.80	1.24	0.320	0.33
125	24.38	10.66	13.9	23.08	1.23	0.277	0.32
126	24.38	9.84	13.8	23.31	1.38	0.341	0.35
127	24.38	10.75	13.4	24.44	1.36	0.300	0.32
128	24.38	10.82	13.9	25.89	1.30	0.319	0.33
129	24.38	10.09	14.0	24.58	1.27	0.333	0.30
130	24.38	9.64	13.8	26.76	1.27	0.325	0.34
131	24.38	8.73	13.5	25.40	1.50	0.347	0.31
132	24.38	8.37	13.8	25.08	1.28	0.320	0.32
133	24.38	8.71	13.3	24.94	1.36	0.370	0.35
134	24.38	8.89	14.6	24.76	1.29	0.312	0.33
135	24.38	8.71	13.8	25.94	1.36	0.340	0.34
136	24.38	8.39	13.8	26.39	1.28	0.305	0.32
213	24.38	8.98	13.7	25.12	1.29	0.295	0.31
214	24.38	9.00	13.8	25.76	1.33	0.309	0.34
215	24.38	10.20	14.3	23.54	1.20	0.312	0.34
216	24.38	10.18	13.6	24.81	1.38	0.309	0.33
217	24.38	8.80	13.4	26.58	1.26	0.298	0.32
218	24.38	10.54	13.9	26.12	1.27	0.291	0.30
219	24.38	10.52	14.0	22.72	1.21	0.295	0.31
220	24.38	9.55	14.4	23.90	1.31	0.311	0.32
221	24.38	9.30	14.0	22.90	1.25	0.288	0.33
222	24.38	9.27	14.8	25.31	1.32	0.287	0.31
223	24.38	9.93	13.8	25.40	1.27	0.305	0.31

224	24.38	8.37	14.2	24.31	1.35	0.307	0.33

Table A.40 Soybean grain yield and nutrient analysis data from Manhattan in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	----------Grain----------		
					N (%)	P (%)	K (%)
201	24.38	2.85	11.6	23.49	5.83	0.697	2.22
202	24.38	2.75	13.5	24.85	6.28	0.748	2.28
203	24.38	2.89	13.2	24.94	6.07	0.812	2.22
204	24.38	2.68	12.3	21.54	5.79	0.713	2.23
205	24.38	2.72	12.0	24.76	6.02	0.724	2.24
206	24.38	2.83	12.7	25.40	5.84	0.711	2.24
207	24.38	2.70	13.3	23.94	5.87	0.704	2.29
208	24.38	2.79	12.4	21.63	5.85	0.722	2.32
209	24.38	2.80	12.1	23.85	5.92	0.684	2.22
210	24.38	2.94	12.2	25.44	6.06	0.769	2.22
211	24.38	2.89	12.5	24.17	6.18	0.746	2.31
212	24.38	2.73	12.4	25.26	5.76	0.701	2.25
301	24.38	3.57	12.0	24.67	5.85	0.688	2.21
302	24.38	3.33	12.8	24.31	6.08	0.648	2.22
303	24.38	3.33	11.7	25.85	6.00	0.628	2.17
304	24.38	3.16	13.5	24.13	5.82	0.737	2.14
305	24.38	3.25	11.0	23.67	5.97	0.658	2.19
306	24.38	3.09	11.4	24.94	5.90	0.692	2.24
307	24.38	3.14	12.0	24.99	5.95	0.724	2.21
308	24.38	3.12	12.7	25.26	5.84	0.706	2.23
309	24.38	3.48	12.4	25.94	5.97	0.703	2.23
310	24.38	3.62	12.1	25.08	6.04	0.678	2.24
311	24.38	3.29	11.1	25.89	6.05	0.692	2.24
312	24.38	3.12	12.9	25.80	6.32	0.708	2.29
325	24.38	2.38	12.3	24.85	6.16	0.648	2.29
326	24.38	2.78	11.6	24.58	5.91	0.597	2.20
327	24.38	2.87	11.4	25.03	6.10	0.639	2.22
328	24.38	2.48	12.6	23.49	6.07	0.688	2.25
329	24.38	2.67	10.8	24.31	6.08	0.631	2.21
330	24.38	2.50	11.8	24.81	6.27	0.665	2.28
331	24.38	2.67	10.7	25.80	6.00	0.600	2.22
332	24.38	2.73	10.7	24.85	6.11	0.672	2.27
333	24.38	2.73	10.0	25.31	5.90	0.623	2.17
334	24.38	2.64	10.6	25.12	6.17	0.622	2.31
335	24.38	2.34	11.3	25.26	6.03	0.608	2.25

336	24.38	2.52	12.2	24.58	5.89	0.684	2.25

Table A.41 Wheat tissue nutrient analysis and biomass yield data from Manhattan in the 2007-08 growing season.

Plot	--------------Flag Leaf--------------			---------------------Whole Plant (Feekes 6)---------------------			
	N	P	K	N	P	K	Biomass
	(%)	(%)	(%)	(%)	(%)	(%)	(kg 0.35m^{-2})
201	3.81	0.226	1.56	3.90	0.283	3.72	0.141
202	3.83	0.259	1.76	3.66	0.275	4.04	0.082
203	4.10	0.274	1.71	3.81	0.296	4.31	0.172
204	3.32	0.253	1.56	2.95	0.386	3.61	0.130
205	4.03	0.282	1.77	3.70	0.358	3.96	0.227
206	3.56	0.272	1.76	3.38	0.332	3.71	0.130
207	3.50	0.276	1.70	2.93	0.340	4.09	0.187
208	3.47	0.285	1.83	3.40	0.393	3.71	0.119
209	3.71	0.271	1.70	3.36	0.355	3.95	0.157
210	2.91	0.253	1.48	2.45	0.258	3.24	0.091
211	3.21	0.210	1.50	3.08	0.314	3.81	0.115
212	3.68	0.265	1.75	3.37	0.319	4.10	0.137
301	3.80	0.262	1.64	2.93	0.240	3.33	0.063
302	3.45	0.234	1.60	3.36	0.206	3.38	0.036
303	3.63	0.258	1.59	3.24	0.245	3.51	0.066
304	2.97	0.209	1.24	3.02	0.280	3.23	0.071
305	3.05	0.250	1.40	2.56	0.227	2.72	0.086
306	3.26	0.247	1.46	2.80	0.320	2.73	0.135
307	3.79	0.275	1.55	3.29	0.386	3.60	0.123
308	3.36	0.268	1.41	2.95	0.376	3.30	0.113
309	3.34	0.285	1.42	2.91	0.350	3.13	0.098
310	3.38	0.259	1.49	2.99	0.326	3.05	0.126
311	3.33	0.246	1.44	3.19	0.283	3.26	0.072
312	3.41	0.257	1.45	3.00	0.265	3.33	0.101
325	3.33	0.238	1.43	3.40	0.268	3.49	0.081
326	3.91	0.256	1.74	3.71	0.353	3.59	0.081
327	3.48	0.249	1.45	3.24	0.309	3.71	0.162
328	4.02	0.252	1.77	3.79	0.289	3.98	0.143
329	3.93	0.263	1.68	3.65	0.296	4.01	0.113
330	3.48	0.278	1.60	2.99	0.268	3.60	0.136
331	3.50	0.225	1.71	3.28	0.249	3.41	0.079
332	3.56	0.257	1.63	2.71	0.312	3.33	0.168
333	3.26	0.224	1.52	3.27	0.300	3.08	0.076
334	3.74	0.261	1.53	2.92	0.253	3.22	0.187
335	3.49	0.222	1.58	3.23	0.227	3.48	0.037

336	3.23	0.259	1.54	2.52	0.254	3.09	0.150

Table A.39 Continued.

Plot	--------Stover (mid bloom)--------	
	P	Dry Weight
	(%)	(kg 0.35m^{-2})
201	0.232	0.141
202	0.138	0.082
203	0.170	0.172
204	0.141	0.13
205	0.183	0.227
206	0.171	0.13
207	0.160	0.187
208	0.132	0.119
209	0.163	0.157
210	0.114	0.091
211	0.134	0.115
212	0.154	0.137
301	0.143	0.063
302	0.183	0.036
303	0.182	0.066
304	0.148	0.071
305	0.178	0.086
306	0.160	0.135
307	0.140	0.123
308	0.185	0.113
309	0.171	0.098
310	0.147	0.126
311	0.179	0.072
312	0.119	0.101
325	0.137	0.081
326	0.137	0.162
327	0.101	0.143
328	0.142	0.113
329	0.137	0.175
330	0.149	0.136
331	0.171	0.079
332	0.131	0.167
333	0.156	0.076
334	0.110	0.187
335	0.135	0.037
336	0.123	0.15

Table A.42 Wheat grain yield and nutrient analysis data from Manhattan in the 2007-08 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
201	24.38	12.23	11.6	60.4	0.308
202	24.38	12.27	11.7	60.5	0.282
203	24.38	13.23	10.8	58.9	0.344
204	24.38	13.00	11.4	61.5	0.431
205	24.38	12.55	10.9	59.9	0.421
206	24.38	11.59	11.4	61.2	0.383
207	24.38	14.36	11.1	60.8	0.378
208	24.38	15.95	11.3	60.9	0.354
209	24.38	12.82	11.1	61.6	0.393
210	24.38	8.86	11.4	62.1	0.392
211	24.38	12.59	11.2	61.4	0.382
212	24.38	13.77	11.3	61.2	0.372
301	24.38	11.00	11.5	61.1	0.281
302	24.38	10.82	11.7	60.2	0.329
303	24.38	12.95	11.3	59.7	0.384
304	24.38	13.27	11.6	60.9	0.257
305	24.38	9.91	11.3	61.5	0.373
306	24.38	12.91	11.3	60.7	0.356
307	24.38	14.45	10.8	60.6	0.419
308	24.38	14.36	11.1	60.5	0.370
309	24.38	-	10.8	58.8	0.433
310	24.38	14.14	11.3	61.0	0.327
311	24.38	14.09	11.1	60.9	0.375
312	24.38	12.55	11.2	61.3	0.300
325	24.38	13.09	11.0	60.8	0.351
326	24.38	14.45	10.6	59.6	0.366
327	24.38	14.82	10.8	61.0	0.377
328	24.38	13.91	10.7	58.6	0.388
329	24.38	16.23	10.2	58.8	0.349
330	24.38	14.41	11.0	60.6	0.314
331	24.38	11.41	10.9	60.5	0.270
332	24.38	13.45	11.1	60.8	0.410
333	24.38	11.68	11.0	60.3	0.388
334	24.38	11.95	11.0	61.1	0.314
335	24.38	10.77	11.0	61.9	0.401
336	24.38	14.00	11.1	61.4	0.322

Table A.43 Grain sorghum tissue nutrient analysis and biomass yield data from Manhattan in the 2008 growing season.

Plot	Flag Leaf	---------------------------Stover (GS 2)---------------------------	
	P	P	Dry Weight
	(%)	(%)	(kg 1.4m^{-2})
113	0.31	0.243	0.444
114	0.32	0.278	0.414
115	0.32	0.272	0.497
116	0.33	0.251	0.424
117	0.33	0.272	0.435
118	0.34	0.361	0.452
119	0.32	0.241	0.477
120	0.35	0.254	0.407
121	0.32	0.245	0.414
122	0.32	0.296	0.479
123	0.33	0.310	0.346
124	0.32	0.245	0.354
225	0.33	0.309	0.411
226	0.31	0.264	0.376
227	0.32	0.259	0.324
228	0.30	0.291	0.324
229	0.33	0.220	0.338
230	0.33	0.302	0.318
231	0.33	0.256	0.400
232	0.31	0.233	0.181
233	0.35	0.233	0.354
234	0.31	0.260	0.348
235	0.31	0.255	0.364
236	0.31	0.233	0.399
314	0.29	0.287	0.350
315	0.31	0.280	0.388
316	0.31	0.264	-
317	0.32	0.299	0.376
318	0.31	0.227	0.393
319	0.30	0.226	0.405
320	0.30	0.257	0.389
321	0.30	0.265	0.341
322	0.30	0.238	0.359
323	0.32	0.247	0.425
324	0.31	0.311	0.380

325	0.29	0.246	0.444

Table A.44 Grain sorghum grain yield and nutrient analysis data from Manhattan in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
113	5.29	4.31	-	-	0.275
114	5.29	4.99	15	24.6	0.294
115	5.29	4.90	14.3	25.7	0.306
116	5.29	4.81	14	25.8	0.296
117	5.29	4.63	14.2	25.2	0.301
118	5.29	5.49	14.9	25.7	0.299
119	5.29	5.04	15.1	25.6	0.310
120	5.29	5.36	14.7	25.9	0.310
121	5.29	5.04	14.3	23.7	0.303
122	5.29	5.27	14.4	25.4	0.291
123	5.29	5.63	14.8	24.7	0.283
124	5.29	5.72	14.2	25.3	0.304
225	5.29	4.81	13.7	25.6	0.290
226	5.29	4.63	14.7	25.2	0.265
227	5.29	4.54	14.2	24.2	0.290
228	5.29	4.40	14.1	24.8	0.286
229	5.29	4.95	15	25.4	0.266
230	5.29	4.63	14	25.2	0.312
231	5.29	5.63	16.1	25.8	0.283
232	5.29	5.31	15.3	25.5	0.280
233	5.29	4.49	-	-	0.278
234	5.29	5.08	14	25.7	0.278
235	5.29	5.36	14.4	26.0	0.312
236	5.29	5.77	14.7	25.1	0.270
314	5.29	6.67	13.9	25.5	0.275
315	5.29	6.54	16.6	25.7	0.259
316	5.29	5.90	15.4	25.7	0.278
317	5.29	5.68	14.2	26.3	0.291
318	5.29	6.04	14.5	25.4	0.257
319	5.29	5.95	14.5	26.1	0.258
320	5.29	5.77	14.4	25.5	0.270
321	5.29	6.04	15.3	25.7	0.266
322	5.29	6.08	15.8	25.6	0.285
323	5.29	5.54	14.3	24.9	0.300
324	5.29	5.36	14.5	25.8	0.283
325	5.29	6.04	14.7	25.6	0.300

Table A.45 Soybean tissue nutrient analysis and biomass yield data from Manhattan in the 2008 growing season.

Plot	------------------------------Stover (V4)------------------------------		Trifoliates (R3)
	P	Dry Weight	P
	(%)	(kg 1.4m^{-2})	(%)
101	0.330	0.168	0.33
102	0.313	0.154	0.35
103	0.318	0.216	0.34
104	0.331	0.205	0.40
105	0.331	0.170	0.35
106	0.346	0.201	0.35
107	0.339	0.187	0.39
108	0.327	0.214	0.43
109	0.306	0.187	0.35
110	0.320	0.164	0.39
111	0.333	0.168	0.34
112	0.327	0.175	0.37
125	0.334	0.171	0.37
126	0.339	0.171	0.32
127	0.325	0.142	0.36
128	0.340	0.185	0.38
129	0.338	0.159	0.35
130	0.321	0.162	0.33
131	0.329	0.175	0.33
132	0.356	0.194	0.36
133	0.344	0.142	0.34
134	0.344	0.195	0.33
135	0.330	0.145	0.35
136	0.327	0.185	0.34
213	0.324	0.195	0.37
214	0.342	0.163	0.35
215	0.328	0.160	0.36
216	0.303	0.160	0.37
217	0.355	0.154	0.36
218	0.330	0.142	0.36
219	0.284	0.186	0.37
220	0.309	0.162	0.34
221	0.313	0.159	0.34
222	0.317	0.150	0.38
223	0.320	0.187	0.34

224	0.327	0.178	0.34

Table A.46 Soybean grain yield and nutrient analysis data from Manhattan in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
101	24.38	13.9	9.2	25.4	0.594
102	24.38	13.1	9.7	25.5	0.589
103	24.38	13.4	10.6	25.3	0.557
104	24.38	13.7	9.5	25.4	0.610
105	24.38	14.4	9.6	25.7	0.608
106	24.38	14.9	9.9	25.3	0.587
107	24.38	14.3	9.4	25.3	0.604
108	24.38	14.7	9.4	25.4	0.604
109	24.38	13.8	10.3	25.0	0.581
110	24.38	14.8	9.3	25.2	0.618
111	24.38	14.7	9.8	25.4	0.598
112	24.38	15.3	9.4	25.2	0.702
125	24.38	13.2	10.7	25.6	0.616
126	24.38	13.7	10.8	25.7	0.626
127	24.38	15.3	10.6	25.0	0.594
128	24.38	14.1	10.5	25.3	0.609
129	24.38	14.1	10.2	25.2	0.609
130	24.38	13.3	10.8	25.3	0.597
131	24.38	13.7	10.4	25.5	0.600
132	24.38	12.6	10.7	25.6	0.602
133	24.38	11.9	10.2	25.8	0.577
134	24.38	15.2	12	25.6	0.604
135	24.38	14.3	11.3	25.4	0.606
136	24.38	13.8	11.4	25.5	0.607
213	24.38	15.0	9.7	25.2	0.569
214	24.38	15.8	9.8	25.3	0.596
215	24.38	15.2	10.5	25.2	0.605
216	24.38	15.9	10.3	25.4	0.573
217	24.38	15.7	10.8	25.3	0.582
218	24.38	15.6	10.4	25.4	0.578
219	24.38	15.1	10.7	25.2	0.549
220	24.38	15.9	11.5	25.4	0.605
221	24.38	15.5	10.8	25.5	0.516
222	24.38	16.0	10.5	24.8	0.569
223	24.38	14.8	11.2	25.0	0.529
224	24.38	15.8	11.2	24.8	0.583

Table A.47 Initial soil sample data from Manhattan Agronomy North Farm.

Plots	Depth (m)	pH	Buffer pH	P (ppm)	K (ppm)	SO_4^{2+} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	OM (%)	Cl^- (ppm)
101-112	0-0.08	4.9	6.1	85	449	7.9	14.3	10.3	3.3	2.7
101-112	0.08-0.15	4.9	6.1	21	249	5.8	10.4	7.5	2.5	2.1
101-112	0.15-0.23	5.3	6.5	8	206	4.7	7.9	6.3	2.3	1.8
101-112	0.23-0.31	5.7	6.7	5	227	5.0	8.0	6.1	2.3	1.8
101-112	0.31-0.61	5.7	6.8	5	275	5.1	7.9	6.8	2.0	1.2
101-112	0.61-0.91	6.3	7.0	4	253	4.7	10.0	4.9	1.3	1.4
113-124	0-0.08	4.9	6.3	72	424	6.1	4.2	19.4	2.6	1.2
113-124	0.08-0.15	4.9	6.2	31	259	4.8	4.6	11.2	2.5	0.8
113-124	0.15-0.23	5.2	6.5	13	212	5.1	5.0	10.6	2.5	1.3
113-124	0.23-0.31	5.7	6.8	6	219	4.3	4.4	10.5	2.5	1.4
113-124	0.31-0.61	6.0	6.9	3	275	4.8	5.6	8.0	1.6	0.5
113-124	0.61-0.91	6.5	-	5	217	4.4	4.0	4.3	0.9	0.8
125-136	0-0.08	5.5	6.6	74	476	5.5	7.4	9.0	2.7	1.5
125-136	0.08-0.15	5.3	6.5	35	298	4.7	8.8	7.5	2.3	1.5
125-136	0.15-0.23	5.7	6.8	8	258	4.4	6.7	5.8	2.4	1.5
125-136	0.23-0.31	6.0	6.8	5	279	4.8	6.6	5.3	1.9	0.9
125-136	0.31-0.61	6.2	7.0	4	295	5.0	8.1	4.3	1.5	1.4
125-136	0.61-0.91	6.4	7.1	4	236	4.4	5.5	7.7	1.0	1.4
201-212	0-0.08	5.4	6.6	52	359	4.6	4.8	9.7	2.5	1.3
201-212	0.08-0.15	5.3	6.4	25	230	4.3	5.2	6.4	2.1	0.7
201-212	0.15-0.23	5.3	6.6	6	250	4.7	6.3	6.1	2.1	1.1
201-212	0.23-0.31	5.3	6.9	3	278	4.3	7.1	4.9	1.8	0.9
201-212	0.31-0.61	6.3	7.0	3	292	4.2	5.3	2.8	1.2	1.8
201-212	0.61-0.91	6.8	-	7	270	3.2	5.7	2.0	0.8	1.1
213-224	0-0.08	5.1	6.4	68	399	7.9	8.7	11.8	2.7	3.2
213-224	0.08-0.15	5.0	6.3	28	243	6.9	6.8	7.9	2.3	1.8
213-224	0.15-0.23	5.3	6.4	11	228	6.2	6.9	8.0	2.4	1.3
213-224	0.23-0.31	5.7	6.6	4	260	7.1	8.6	7.2	2.5	2.1
213-224	0.31-0.61	6.0	6.9	3	313	7.1	11.2	6.3	1.8	2.5
213-224	0.61-0.91	6.4	7.1	4	319	5.1	10.1	4.1	1.1	2.9
225-236	0-0.08	5.4	6.5	28	402	4.9	4.4	7.3	2.6	1.3
225-236	0.08-0.15	5.3	6.6	9	242	4.6	5.1	6.3	2.1	1.3
225-236	0.15-0.23	5.6	6.7	6	249	4.7	4.8	5.6	1.9	1.5
225-236	0.23-0.31	5.8	6.8	4	264	4.8	5.2	5.4	1.7	1.3

225-236	0.31-0.61	6.2	7.0	4	273	4.0	5.1	3.1	1.3	1.4
225-236	0.61-0.91	6.5	-	3	221	4.0	5.0	2.3	0.9	1.2
301-312	0-0.08	5.5	6.6	18	391	5.7	4.4	5.7	2.2	2.1
301-312	0.08-0.15	5.4	6.5	5	268	4.8	8.0	4.7	2.0	1.3
301-312	0.15-0.23	5.7	6.7	3	291	5.3	6.9	3.8	1.7	1.9
301-312	0.23-0.31	6.1	6.9	3	287	5.0	5.4	3.2	1.6	1.5
301-312	0.31-0.61	6.2	6.9	3	264	4.4	6.2	1.6	1.3	1.9
301-312	0.61-0.91	6.5	-	4	202	4.3	6.0	1.1	0.8	1.1
313-324	0-0.08	5.3	6.2	68	382	5.3	6.0	8.0	2.3	1.7
313-324	0.08-0.15	5.3	6.3	14	238	4.9	5.6	8.6	2.1	1.0
313-324	0.15-0.23	5.7	6.5	5	218	3.8	5.6	8.7	2.1	0.8
313-324	0.23-0.31	6.2	6.7	3	268	4.8	5.4	6.6	1.6	0.8
313-324	0.31-0.61	6.6	-	3	251	3.6	5.0	3.2	1.1	0.3
313-324	0.61-0.91	6.6	-	4	183	4.0	4.6	3.1	0.7	0.5
325-336	0-0.08	5.5	7.1	35	311	4.2	5.6	7.5	2.4	0.8
325-336	0.08-0.15	5.4	6.2	12	236	3.9	5.3	6.2	2.0	0.8
325-336	0.15-0.23	5.6	6.1	4	246	4.6	5.8	5.1	2.2	0.8
325-336	0.23-0.31	6.1	6.7	4	295	4.3	5.1	4.2	1.9	1.0
325-336	0.31-0.61	6.4	6.9	3	257	4.1	6.5	3.1	1.2	0.4
325-336	0.61-0.91	6.6	-	3	217	3.7	6.3	2.7	0.9	1.1

Table A.48 Soil sample data from Manhattan Agronomy North Farm collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

Plot	Depth (m)	Location	P (ppm)
101	0-0.08	Row	63
101	0.08-0.15	Row	23
101	0.15-0.23	Row	4
101	0.23-0.31	Row	3
101	0.31-0.61	Row	3
101	0-0.08	Row Middle	70
101	0.08-0.15	Row Middle	18
101	0.15-0.23	Row Middle	5
101	0.23-0.31	Row Middle	3
101	0.31-0.61	Row Middle	3
104	0-0.08	Row	62
104	0.08-0.15	Row	36
104	0.15-0.23	Row	8
104	0.23-0.31	Row	5
104	0.31-0.61	Row	4
104	0-0.08	Row Middle	64
104	0.08-0.15	Row Middle	47
104	0.15-0.23	Row Middle	20
104	0.23-0.31	Row Middle	5
104	0.31-0.61	Row Middle	7
105	0-0.08	Row	78
105	0.08-0.15	Row	42
105	0.15-0.23	Row	9
105	0.23-0.31	Row	4
105	0.31-0.61	Row	4
105	0-0.08	Row Middle	73
105	0.08-0.15	Row Middle	20
105	0.15-0.23	Row Middle	7
105	0.23-0.31	Row Middle	5
105	0.31-0.61	Row Middle	3
107	0-0.08	Row	65
107	0.08-0.15	Row	49
107	0.15-0.23	Row	12
107	0.23-0.31	Row	5

107	0.31-0.61	Row	6
107	0-0.08	Row Middle	76
107	0.08-0.15	Row Middle	46
107	0.15-0.23	Row Middle	13
107	0.23-0.31	Row Middle	5
107	0.31-0.61	Row Middle	5
110	0-0.08	Row	74
110	0.08-0.15	Row	44
110	0.15-0.23	Row	30
110	0.23-0.31	Row	9
110	0.31-0.61	Row	5
110	0-0.08	Row Middle	71
110	0.08-0.15	Row Middle	37
110	0.15-0.23	Row Middle	11
110	0.23-0.31	Row Middle	5
110	0.31-0.61	Row Middle	5
125	0-0.08	Row	51
125	0.08-0.15	Row	122
125	0.15-0.23	Row	72
125	0.23-0.31	Row	19
125	0.31-0.61	Row	7
125	0-0.08	Row Middle	53
125	0.08-0.15	Row Middle	28
125	0.15-0.23	Row Middle	33
125	0.23-0.31	Row Middle	10
125	0.31-0.61	Row Middle	7
128	0-0.08	Row	37
128	0.08-0.15	Row	88
128	0.15-0.23	Row	11
128	0.23-0.31	Row	8
128	0.31-0.61	Row	4
128	0-0.08	Row Middle	42
128	0.08-0.15	Row Middle	20
128	0.15-0.23	Row Middle	10
128	0.23-0.31	Row Middle	5
128	0.31-0.61	Row Middle	9
129	0-0.08	Row	66

129	0.08-0.15	Row	31
129	0.15-0.23	Row	19
129	0.23-0.31	Row	5
129	0.31-0.61	Row	3
129	0-0.08	Row Middle	48
129	0.08-0.15	Row Middle	18
129	0.15-0.23	Row Middle	11
129	0.23-0.31	Row Middle	5
129	0.31-0.61	Row Middle	5
131	0-0.08	Row	88
131	0.08-0.15	Row	18
131	0.15-0.23	Row	6
131	0.23-0.31	Row	6
131	0.31-0.61	Row	8
131	0-0.08	Row Middle	60
131	0.08-0.15	Row Middle	10
131	0.15-0.23	Row Middle	7
131	0.23-0.31	Row Middle	4
131	0.31-0.61	Row Middle	5
136	0-0.08	Row	52
136	0.08-0.15	Row	36
136	0.15-0.23	Row	7
136	0.23-0.31	Row	13
136	0.31-0.61	Row	5
136	0-0.08	Row Middle	72
136	0.08-0.15	Row Middle	39
136	0.15-0.23	Row Middle	18
136	0.23-0.31	Row Middle	7
136	0.31-0.61	Row Middle	5
215	0-0.08	Row	37
215	0.08-0.15	Row	24
215	0.15-0.23	Row	5
215	0.23-0.31	Row	3
215	0.31-0.61	Row	4
215	0-0.08	Row Middle	49
215	0.08-0.15	Row Middle	17
215	0.15-0.23	Row Middle	6

215	0.23-0.31	Row Middle	4
215	0.31-0.61	Row Middle	4
217	0-0.08	Row	50
217	0.08-0.15	Row	14
217	0.15-0.23	Row	7
217	0.23-0.31	Row	5
217	0.31-0.61	Row	4
217	0-0.08	Row Middle	38
217	0.08-0.15	Row Middle	20
217	0.15-0.23	Row Middle	11
217	0.23-0.31	Row Middle	3
217	0.31-0.61	Row Middle	2
218	0-0.08	Row	20
218	0.08-0.15	Row	37
218	0.15-0.23	Row	15
218	0.23-0.31	Row	3
218	0.31-0.61	Row	3
218	0-0.08	Row Middle	24
218	0.08-0.15	Row Middle	11
218	0.15-0.23	Row Middle	5
218	0.23-0.31	Row Middle	3
218	0.31-0.61	Row Middle	3
221	0-0.08	Row	23
221	0.08-0.15	Row	12
221	0.15-0.23	Row	3
221	0.23-0.31	Row	3
221	0.31-0.61	Row	3
221	0-0.08	Row Middle	20
221	0.08-0.15	Row Middle	13
221	0.15-0.23	Row Middle	4
221	0.23-0.31	Row Middle	3
221	0.31-0.61	Row Middle	3
223	0-0.08	Row	31
223	0.08-0.15	Row	14
223	0.15-0.23	Row	3
223	0.23-0.31	Row	4
223	0.31-0.61	Row	2

223	0-0.08	Row Middle	23
223	0.08-0.15	Row Middle	12
223	0.15-0.23	Row Middle	5
223	0.23-0.31	Row Middle	3
223	0.31-0.61	Row Middle	2

Table A.49 Additional plot soil sample data and re-sampled plots from Manhattan collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

Plot	Depth (m)	Location	P (ppm)
104	0-0.08	Row Middle	56
104	0.08-0.15	Row Middle	25
105	0-0.08	Row Middle	65
105	0.08-0.15	Row Middle	25
107	0-0.08	Row Middle	69
107	0.08-0.15	Row Middle	40
108	0-0.08	Row	82
108	0.08-0.15	Row	35
108	0.15-0.23	Row	30
108	0-0.08	Row Middle	89
108	0.08-0.15	Row Middle	50
108	0.15-0.23	Row Middle	26
110	0-0.08	Row	64
110	0.08-0.15	Row	32
110	0-0.08	Row Middle	65
110	0.08-0.15	Row Middle	35
125	0-0.08	Row	51
125	0.08-0.15	Row	100
128	0-0.08	Row	53
128	0.08-0.15	Row	54
133	0-0.08	Row	93
133	0.08-0.15	Row	36
133	0.15-0.23	Row	35
133	0-0.08	Row Middle	76
133	0.08-0.15	Row Middle	56
133	0.15-0.23	Row Middle	34
136	0-0.08	Row Middle	67
136	0.08-0.15	Row Middle	32
215	0-0.08	Row	63
215	0.08-0.15	Row	16
217	0-0.08	Row Middle	35
217	0.08-0.15	Row Middle	18
218	0-0.08	Row	29
218	0.08-0.15	Row	43

218	0-0.08	Row Middle	29
218	0.08-0.15	Row Middle	14
221	0-0.08	Row	30
221	0.08-0.15	Row	10
221	0-0.08	Row Middle	29
221	0.08-0.15	Row Middle	14
223	0-0.08	Row	36
223	0.08-0.15	Row	90
223	0-0.08	Row Middle	34
223	0.08-0.15	Row Middle	10
224	0-0.08	Row	56
224	0.08-0.15	Row	13
224	0.15-0.23	Row	9
224	0-0.08	Row Middle	55
224	0.08-0.15	Row Middle	21
224	0.15-0.23	Row Middle	16

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P Management in Reduced Tillage (Tribune, KS)

Plot length = 120 ft, Alley = 40 ft

Trt.	Starter P	Broadcast P	Deep Band P	Total P	Starter P	Broadcast P	Deep Band P	Total P	Total P
	Wheat				Sorghum				Fallow
1	0	0	0	0	0	0	0	0	0
2	20	0	0	20	20	0	0	20	0
3	0	40	0	40	0	40	0	40	0
4	20	20	0	40	20	20	0	40	0
5	0	0	40	40	0	0	40	40	0
6	20	0	20	40	20	0	20	40	0
7	0	80	0	80	0	80	0	80	0
8	20	60	0	80	20	60	0	80	0
9	0	0	80	80	0	0	80	80	0
10	20	0	60	80	20	0	60	80	0

N 

B	401	402	403	404	405	406	407	408	409	410	B	B	411	412	413	414	415	416	417	418	419	420	B	B	421	422	423	424	425	426	427	428	429	430	B
	8	5	1	3	6	7	10	9	2	4			5	3	4	10	9	2	7	6	1	8			8	6	5	9	3	1	7	4	10	2	

Sorghum (2006) – Fallow – Wheat   Fallow (2006) –Wheat – Sorghum   Wheat (05-06) – Sorghum – Fallow

B	301	302	303	304	305	306	307	308	309	310	B	B	311	312	313	314	315	316	317	318	319	320	B	B	321	322	323	324	325	326	327	328	329	330	B
	2	8	4	3	9	10	6	1	5	7			4	5	8	10	6	2	1	3	9	7			10	8	3	5	6	1	7	2	9	4	

Sorghum (2006) – Fallow – Wheat   Wheat (05-06) – Sorghum – Fallow   Fallow (2006) –Wheat – Sorghum

B	201	202	203	204	205	206	207	208	209	210	B	B	211	212	213	214	215	216	217	218	219	220	B	B	221	222	223	224	225	226	227	228	229	230	B
	3	8	6	7	1	4	10	2	5	9			9	3	5	1	10	6	8	2	7	4			9	2	5	10	6	8	7	4	3	1	

Fallow (2006) –Wheat – Sorghum   Sorghum (2006) – Fallow – Wheat   Wheat (05-06) – Sorghum – Fallow

B	101	102	103	104	105	106	107	108	109	110	B	B	111	112	113	114	115	116	117	118	119	120	B	B	121	122	123	124	125	126	127	128	129	130	B
	8	2	6	4	5	3	9	10	7	1			6	2	5	10	7	9	1	3	8	4			3	8	5	10	2	6	9	1	4	7	

Wheat (05-06) – Sorghum – Fallow   Fallow (2006) –Wheat – Sorghum   Sorghum (2006) – Fallow – Wheat

Table A.50 Wheat tissue nutrient analysis data from Tribune in the 2005-06 growing season.

Plot	----------Flag Leaf----------		
	N	P	K
	(%)	(%)	(%)
101	3.37	0.279	1.86
102	3.70	0.323	1.93
103	3.70	0.338	2.00
104	3.62	0.306	1.89
105	3.79	0.312	1.97
106	3.66	0.297	1.87
107	3.61	0.288	1.80
108	3.62	0.293	1.85
109	3.55	0.267	1.81
110	3.79	0.308	2.03
221	3.69	0.275	2.01
222	3.67	0.267	1.80
223	3.64	0.266	1.90
224	3.73	0.269	1.95
225	3.73	0.280	1.89
226	3.20	0.237	1.72
227	3.64	0.266	2.00
228	3.66	0.275	1.94
229	3.74	0.268	2.03
230	3.66	0.258	1.93
311	3.58	0.254	1.92
312	3.62	0.244	1.97
313	3.46	0.223	1.77
314	3.57	0.243	1.95
315	3.58	0.242	1.88
316	3.48	0.225	1.63
317	3.60	0.221	1.83
318	3.74	0.213	1.90
319	3.52	0.204	1.79
320	3.62	0.239	1.86
421	3.73	0.300	1.93
422	3.54	0.313	1.98
423	3.42	0.252	1.85
424	3.40	0.255	1.83
425	3.44	0.253	1.93

426	3.44	0.266	1.98
427	3.46	0.267	1.89
428	3.46	0.256	1.91
429	3.63	0.274	1.89
430	3.71	0.286	2.09

Table A.51 Wheat grain yield and nutrient analysis data from Tribune in the 2005-06 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	---Grain---		
					N (%)	P (%)	K (%)
101	36.58	5.99	10.4	25.21	2.98	0.390	0.32
102	36.58	4.54	10.1	24.94	3.17	0.376	0.30
103	36.58	4.44	9.9	24.72	3.28	0.405	0.31
104	36.58	4.67	10.4	24.81	3.23	0.390	0.30
105	36.58	4.63	10.2	24.99	3.19	0.383	0.29
106	36.58	4.49	9.9	24.67	3.15	0.376	0.31
107	36.58	3.99	9.5	25.85	3.17	0.386	0.31
108	36.58	4.94	10.1	24.53	3.26	0.432	0.32
109	36.58	5.40	10.5	24.58	3.18	0.433	0.34
110	36.58	5.26	10.2	24.90	3.00	0.417	0.38
221	36.58	3.17	11.8	24.22	2.82	0.285	0.31
222	36.58	4.40	11.8	24.58	2.94	0.361	0.36
223	36.58	6.21	11.9	24.90	2.89	0.337	0.37
224	36.58	6.80	11.9	24.76	2.73	0.329	0.34
225	36.58	6.94	12.5	24.72	2.73	0.330	0.33
226	36.58	6.58	12.1	25.08	2.73	0.339	0.35
227	36.58	5.90	12.5	24.76	2.70	0.309	0.33
228	36.58	5.80	12.1	25.03	2.69	0.306	0.33
229	36.58	5.40	12.2	24.94	2.91	0.340	0.39
230	36.58	5.22	12.8	24.22	2.82	0.317	0.35
311	36.58	6.76	11.6	24.81	2.82	0.356	0.33
312	36.58	5.85	11.9	25.03	2.88	0.340	0.33
313	36.58	7.03	12.3	24.58	2.88	0.326	0.32
314	36.58	6.35	12.0	24.81	2.84	0.302	0.31
315	36.58	6.21	11.9	24.94	2.96	0.308	0.31
316	36.58	6.30	11.9	24.94	2.95	0.293	0.30
317	36.58	5.31	12.0	25.49	2.90	0.294	0.32
318	36.58	5.94	12.2	24.94	2.93	0.299	0.33
319	36.58	5.53	12.1	25.40	2.83	0.279	0.31
320	36.58	6.39	12.1	25.26	2.96	0.302	0.32
421	36.58	3.27	11.4	25.21	3.07	0.379	0.34
422	36.58	3.17	11.7	24.76	3.13	0.369	0.30
423	36.58	2.90	11.6	24.99	3.05	0.362	0.33
424	36.58	3.45	11.7	24.76	2.99	0.371	0.33
425	36.58	2.81	11.6	25.03	3.02	0.333	0.30

426	36.58	2.90	11.4	25.21	2.98	0.357	0.32
427	36.58	2.04	11.7	24.72	3.10	0.408	0.36
428	36.58	3.40	11.4	25.44	2.90	0.341	0.31
429	36.58	3.17	11.5	25.17	3.02	0.353	0.31
430	36.58	3.81	11.4	25.12	3.02	0.365	0.31

Table A.52 Grain sorghum tissue nutrient analysis data from Tribune in the 2006 growing season.

Plot	--------Flag Leaf--------		
	N (%)	P (%)	K (%)
121	1.70	0.181	1.67
122	2.08	0.210	1.56
123	2.10	0.213	1.53
124	1.96	0.223	1.65
125	2.00	0.205	1.58
126	2.14	0.216	1.52
127	2.15	0.221	1.54
128	2.14	0.202	1.47
129	2.31	0.210	1.41
130	2.28	0.211	1.45
211	2.16	0.211	1.54
212	2.22	0.190	1.54
213	2.21	0.171	1.61
214	2.12	0.166	1.63
215	2.16	0.181	1.67
216	2.15	0.175	1.57
217	2.17	0.179	1.60
218	2.08	0.160	1.51
219	2.33	0.185	1.49
220	2.21	0.179	1.58
301	1.79	0.183	1.58
302	1.83	0.208	1.62
303	1.80	0.192	1.69
304	2.00	0.199	1.73
305	2.13	0.221	1.65
306	2.13	0.216	1.62
307	2.10	0.213	1.50
308	2.06	0.189	1.59
309	2.18	0.184	1.70
310	2.24	0.201	1.61
401	1.93	0.246	1.67
402	1.99	0.227	1.59
403	1.86	0.203	1.47
404	2.01	0.225	1.63
405	1.94	0.212	1.62
406	2.02	0.217	1.49
407	2.06	0.244	1.45

408	2.18	0.238	1.53
409	1.96	0.225	1.68
410	2.14	0.240	1.56

Table A.53 Grain sorghum grain yield and nutrient analysis data from Tribune in the 2006 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	----------Grain----------		
					N (%)	P (%)	K (%)
121	32.49	8.30	12.2	27.30	1.88	0.288	0.38
122	32.46	7.66	12.0	26.98	1.90	0.275	0.37
123	32.58	8.34	11.8	26.85	1.84	0.292	0.37
124	32.49	10.34	12.0	27.21	1.68	0.290	0.37
125	32.58	12.56	11.8	27.26	1.86	0.297	0.37
126	32.61	11.93	11.8	27.26	1.82	0.313	0.40
127	32.49	13.29	11.8	27.35	1.84	0.320	0.39
128	32.52	17.69	11.9	27.44	1.79	0.269	0.34
129	32.52	20.18	12.1	27.57	1.78	0.325	0.44
130	32.16	17.37	11.9	27.44	1.81	0.298	0.38
211	28.83	15.24	11.9	27.53	1.89	0.263	0.30
212	28.93	17.19	11.9	27.39	1.77	0.252	0.31
213	29.20	18.96	12.2	27.44	1.76	0.250	0.34
214	29.41	19.36	12.2	27.48	1.57	0.241	0.34
215	29.44	21.95	12.2	27.53	1.46	0.210	0.30
216	29.50	22.09	12.2	27.44	1.49	0.179	0.25
217	29.54	19.73	12.3	27.30	1.44	0.187	0.28
218	29.50	19.18	12.3	27.03	1.44	0.205	0.33
219	29.60	20.00	12.1	27.30	1.51	0.183	0.28
220	29.66	20.09	12.1	27.35	1.52	0.215	0.32
301	33.28	12.24	11.8	27.48	1.72	0.190	0.24
302	33.41	7.89	11.7	27.53	1.85	0.269	0.31
303	33.28	4.85	11.6	27.26	1.87	0.307	0.36
304	33.28	11.79	11.8	27.53	1.88	0.275	0.33
305	33.13	12.29	11.9	27.53	1.88	0.262	0.29
306	33.10	14.69	11.7	27.62	1.88	0.251	0.29
307	32.98	10.66	11.6	27.57	1.87	0.233	0.26
308	32.98	17.64	11.8	27.48	1.73	0.232	0.29
309	33.07	16.96	12.0	27.44	1.74	0.206	0.28
310	33.10	16.60	12.0	27.48	1.82	0.253	0.30
401	33.10	7.53	11.8	27.57	1.82	0.268	0.31
402	33.28	7.21	11.7	27.57	1.91	0.272	0.30
403	33.71	2.81	11.7	27.53	1.88	0.283	0.32
404	33.65	11.88	11.7	27.62	1.84	0.270	0.31
405	33.71	7.89	11.8	27.57	1.76	0.272	0.31

406	33.50	10.02	11.7	27.53	1.76	0.295	0.33
407	33.59	5.94	12.0	27.53	1.80	0.278	0.31
408	33.65	12.52	11.9	27.75	1.86	0.219	0.24
409	33.53	13.74	11.9	27.57	1.78	0.220	0.25
410	33.53	16.05	12.0	27.71	1.74	0.210	0.24

Table A.54 Wheat tissue nutrient analysis data from Tribune in the 2006-07 growing season.

Plot	----------Flag Leaf----------			----------Stover (mid bloom)----------		
	N	P	K	N	P	K
	(%)	(%)	(%)	(%)	(%)	(%)
111	3.64	0.265	1.93	1.11	0.208	1.09
112	3.55	0.260	2.04	0.83	0.150	1.17
113	3.57	0.264	1.85	0.89	0.153	1.09
114	3.46	0.267	1.72	1.14	0.209	1.69
115	3.45	0.294	1.94	1.02	0.177	1.39
116	3.49	0.273	1.73	0.76	0.141	1.23
117	3.47	0.257	1.77	1.06	0.140	1.58
118	3.51	0.259	1.92	1.18	0.158	1.82
119	3.78	0.262	2.15	1.41	0.169	2.06
120	3.78	0.253	2.12	1.09	0.163	1.56
201	3.42	0.263	1.84	0.76	0.115	1.14
202	3.94	0.277	2.05	1.25	0.184	1.66
203	3.88	0.265	2.14	1.50	0.205	1.84
204	3.80	0.268	1.88	1.18	0.177	1.92
205	3.90	0.269	2.00	1.37	0.178	1.80
206	3.83	0.261	1.77	1.10	0.146	1.97
207	3.71	0.269	1.83	1.14	0.225	1.50
208	3.81	0.254	1.92	1.42	0.192	1.72
209	3.61	0.261	1.82	1.48	0.165	1.51
210	3.54	0.264	1.68	1.39	0.179	1.45
321	3.37	0.217	1.46	1.30	0.147	1.82
322	3.45	0.213	1.59	1.40	0.202	1.78
323	3.41	0.205	1.38	1.36	0.162	1.58
324	3.17	0.195	1.31	1.29	0.155	1.61
325	3.18	0.180	1.29	1.36	0.184	1.55
326	3.31	0.187	1.33	1.04	0.104	1.30
327	3.34	0.203	1.45	0.91	0.112	1.08
328	3.32	0.198	1.33	1.32	0.151	1.54
329	3.74	0.220	1.68	1.37	0.145	1.68
330	3.60	0.222	1.68	1.14	0.118	1.47
411	3.57	0.275	1.81	1.17	0.201	1.91
412	3.86	0.286	1.94	1.28	0.234	1.94
413	3.81	0.282	1.90	1.37	0.223	2.35
414	3.88	0.281	1.76	1.34	0.231	1.93
415	3.58	0.276	1.70	1.20	0.237	1.80

416	3.60	0.279	1.77	-	-	-
417	3.74	0.270	1.77	1.22	0.217	1.54
418	3.94	0.271	1.73	1.22	0.214	2.01
419	3.69	0.251	1.66	1.81	0.249	2.69
420	3.69	0.268	1.66	1.35	0.202	2.68

Table A.55 Wheat grain yield and nutrient analysis data from Tribune in the 2006-07 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	---------------------Grain---------------------		
					N (%)	P (%)	K (%)
111	29.20	27.48	11.6	27.21	2.98	0.390	0.32
112	28.93	25.62	11.6	26.89	3.17	0.376	0.31
113	29.29	26.35	11.8	27.26	3.28	0.405	0.31
114	29.17	27.44	11.6	26.53	3.23	0.390	0.30
115	29.08	28.53	11.5	26.44	3.19	0.383	0.29
116	28.99	28.03	11.6	25.99	3.15	0.376	0.31
117	28.96	28.80	11.6	26.48	3.17	0.386	0.31
118	28.83	26.30	11.4	25.58	3.26	0.432	0.32
119	28.83	23.67	11.2	25.67	3.18	0.433	0.34
120	28.77	21.99	11.2	25.17	3.00	0.417	0.38
201	29.54	32.11	12.3	26.48	2.82	0.285	0.31
202	29.47	28.25	13.1	25.40	2.94	0.361	0.36
203	29.60	26.26	12.7	25.49	2.89	0.337	0.37
204	29.50	25.67	12.4	24.99	2.73	0.329	0.34
205	29.41	25.31	11.5	24.40	2.73	0.330	0.33
206	29.26	25.53	11.5	24.94	2.73	0.339	0.35
207	29.23	26.53	11.1	24.76	2.70	0.309	0.33
208	29.29	26.03	12.1	25.17	2.69	0.306	0.33
209	29.35	29.25	13.3	25.21	2.91	0.340	0.39
210	29.50	28.53	11.8	26.26	2.82	0.317	0.35
321	28.77	29.34	12.5	26.12	2.82	0.356	0.33
322	28.53	28.84	12.4	26.53	2.88	0.340	0.33
323	28.90	26.26	12.3	26.76	2.88	0.326	0.32
324	28.77	24.44	12.6	26.58	2.84	0.302	0.31
325	28.86	28.98	12.9	26.30	2.96	0.308	0.32
326	28.71	21.68	12.1	25.76	2.95	0.293	0.30
327	28.56	25.62	12.9	26.67	2.90	0.294	0.32
328	28.53	24.72	13.8	25.76	2.93	0.299	0.33
329	28.44	23.99	14.5	25.35	2.83	0.279	0.31
330	28.47	22.31	13.8	25.49	2.96	0.302	0.32
411	28.44	28.25	12.9	25.76	3.07	0.379	0.34
412	28.53	29.07	12.6	25.44	3.13	0.369	0.31
413	28.99	27.80	11.5	25.08	3.05	0.362	0.33
414	29.17	29.89	11.4	25.80	2.99	0.371	0.33
415	29.14	27.94	11.1	25.08	3.02	0.333	0.30

416	29.08	28.07	11.3	25.03	2.98	0.357	0.32
417	29.08	25.35	11.0	24.13	3.10	0.408	0.36
418	29.11	27.21	10.7	24.04	2.90	0.341	0.31
419	28.99	26.94	10.9	25.26	3.02	0.353	0.31
420	29.05	23.81	10.9	24.31	3.02	0.365	0.31

Table A.56 Grain sorghum tissue nutrient analysis and biomass yield data from Tribune in the 2007 growing season.

Plot	--------------Flag Leaf--------------			---------------------Stover (GS3)---------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	(kg $1.4m^{-2}$)
101	2.73	0.392	1.26	3.10	0.342	4.22	0.15
102	2.55	0.359	1.15	3.06	0.279	4.23	0.16
103	2.66	0.326	1.25	2.93	0.260	3.98	0.17
104	2.63	0.336	1.35	3.31	0.301	4.20	0.17
105	2.93	0.338	1.27	2.83	0.248	4.36	0.17
106	2.67	0.346	1.23	2.94	0.264	4.34	0.16
107	2.53	0.305	1.29	3.14	0.268	3.63	0.16
108	2.58	0.320	1.27	3.02	0.253	3.86	0.19
109	2.62	0.323	1.18	2.76	0.264	4.35	0.18
110	2.46	0.285	1.25	2.65	0.296	4.17	0.17
221	2.43	0.268	1.24	3.16	0.275	3.88	0.18
222	2.55	0.266	1.22	2.66	0.301	3.55	0.18
223	2.53	0.261	1.19	3.60	0.416	3.78	0.15
224	2.59	0.271	1.14	2.79	0.275	3.64	0.14
225	2.91	0.300	1.14	3.50	0.449	3.71	0.14
226	2.62	0.271	1.13	2.75	0.332	3.76	0.14
227	2.57	0.290	1.13	2.71	0.323	4.04	0.12
228	2.90	0.286	1.08	2.94	0.276	4.18	0.14
229	2.83	0.265	1.13	3.21	0.346	3.77	0.11
230	2.59	0.239	1.12	3.40	0.409	3.89	0.11
311	2.57	0.275	1.08	2.80	0.294	4.30	0.15
312	2.70	0.279	1.19	2.74	0.260	4.09	0.15
313	3.05	0.317	1.39	3.09	0.313	3.95	0.13
314	3.09	0.311	1.38	2.67	0.260	4.27	0.11
315	2.79	0.262	1.16	2.97	0.286	4.66	0.12
316	2.76	0.238	1.24	2.67	0.246	4.11	0.12
317	3.08	0.283	1.32	2.05	0.194	4.84	0.13
318	2.74	0.227	1.33	2.73	0.249	4.36	0.13
319	2.70	0.252	1.27	2.98	0.284	4.16	0.12
320	2.93	0.270	1.21	2.78	0.283	4.75	0.10
421	2.70	0.338	1.23	2.90	0.303	3.20	0.18
422	2.49	0.302	1.29	2.84	0.263	3.45	0.19
423	2.71	0.296	1.16	2.60	0.257	3.52	0.17
424	2.99	0.318	1.30	3.03	0.332	3.30	0.15
425	2.74	0.277	1.25	2.64	0.267	3.24	0.15

426	2.72	0.251	1.11	2.91	0.348	3.77	0.13
427	3.05	0.285	1.26	3.20	0.353	3.70	0.11
428	2.84	0.257	1.27	3.05	0.287	3.58	0.12
429	2.89	0.257	1.21	3.21	0.307	3.53	0.10
430	2.76	0.254	1.25	2.90	0.315	3.98	0.13

Table A.53 Continued.

Plot	----------Stover (mid bloom)----------			
	N	P	K	Dry Weight
	(%)	(%)	(%)	(kg 1.4m^{-2})
101	0.46	0.061	3.24	0.91
102	0.49	0.050	3.04	0.83
103	0.55	0.073	3.09	0.55
104	0.79	0.079	2.84	0.83
105	0.61	0.059	2.93	0.81
106	0.63	0.068	4.53	0.59
107	0.49	0.058	4.06	0.68
108	0.48	0.054	3.15	0.70
109	0.46	0.042	3.33	0.62
110	0.38	0.029	3.54	0.70
221	0.43	0.031	3.15	0.71
222	0.41	0.036	2.38	0.90
223	0.43	0.036	2.89	0.88
224	0.60	0.045	2.41	0.93
225	0.60	0.052	2.57	0.64
226	0.54	0.042	2.68	0.84
227	0.74	0.065	2.66	1.01
228	0.70	0.057	3.23	0.60
229	0.66	0.053	2.25	0.67
230	0.51	0.041	2.95	0.69
311	0.53	0.051	2.89	0.65
312	0.56	0.033	3.63	0.64
313	0.69	0.036	3.16	0.75
314	0.59	0.027	3.63	0.66
315	0.55	0.029	3.41	0.64
316	0.64	0.031	3.46	0.67
317	0.64	0.027	3.14	0.52
318	0.67	0.038	2.99	0.77
319	0.57	0.029	4.05	0.65
320	0.76	0.040	2.75	0.64
421	0.50	0.045	4.06	0.45
422	0.53	0.037	3.56	0.66
423	0.56	0.035	2.35	0.69
424	0.53	0.035	2.83	0.58
425	0.81	0.075	2.95	0.70
426	0.53	0.038	3.11	0.65

427	0.51	0.044	3.65	0.70
428	0.53	0.033	4.71	0.54
429	0.55	0.038	4.29	0.47
430	-	-	-	0.68

Table A.57 Grain sorghum grain yield and nutrient analysis data from Tribune in the 2007 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	---------------------Grain---------------------		
					N (%)	P (%)	K (%)
101	15.85	11.75	11.0	27.53	1.42	0.258	0.39
102	15.85	15.92	10.2	27.48	1.47	0.304	0.39
103	16.15	8.21	9.6	27.03	1.80	0.365	0.44
104	17.01	6.62	9.5	26.98	1.93	0.350	0.45
105	17.10	12.11	10.0	27.16	1.64	0.318	0.42
106	16.55	12.43	9.4	27.12	1.78	0.326	0.39
107	16.95	9.25	9.4	26.94	1.85	0.322	0.41
108	16.73	11.34	9.7	27.12	1.73	0.339	0.41
109	16.67	13.70	10.0	27.21	1.65	0.320	0.43
110	16.52	11.84	9.5	27.03	1.76	0.347	0.41
221	21.00	21.27	10.1	27.57	1.60	0.263	0.38
222	19.20	20.23	10.3	27.71	1.58	0.223	0.35
223	19.11	13.06	10.6	27.62	1.50	0.240	0.36
224	15.54	16.51	10.6	27.53	1.53	0.281	0.37
225	15.67	15.69	10.7	27.62	1.44	0.244	0.36
226	15.73	16.19	10.7	27.62	1.44	0.248	0.35
227	18.14	11.47	10.9	27.62	1.49	0.231	0.36
228	18.71	15.92	10.7	27.44	1.40	0.199	0.35
229	19.26	18.00	10.7	27.57	1.47	0.183	0.33
230	19.84	20.04	10.8	27.53	1.44	0.205	0.35
311	20.48	21.95	10.6	27.62	1.39	0.234	0.37
312	20.60	21.63	10.5	27.66	1.40	0.214	0.34
313	20.51	17.55	10.2	27.39	1.42	0.212	0.32
314	19.96	18.64	10.8	27.53	1.46	0.212	0.36
315	20.30	18.50	10.5	27.62	1.47	0.165	0.35
316	20.42	17.78	10.5	27.57	1.44	0.175	0.34
317	20.45	13.33	10.4	27.30	1.36	0.142	0.32
318	19.69	16.92	10.3	27.48	1.47	0.155	0.32
319	21.15	19.41	10.7	27.44	1.45	0.163	0.33
320	21.12	15.69	10.8	27.26	1.36	0.194	0.34
421	20.63	15.65	10.1	27.30	1.64	0.284	0.40
422	20.79	15.74	10.0	27.30	1.79	0.287	0.39
423	20.67	18.50	10.1	27.39	1.72	0.280	0.36
424	20.51	16.82	10.6	27.53	1.56	0.281	0.36
425	20.97	17.37	10.3	27.53	1.57	0.230	0.36

426	21.03	16.24	10.4	27.39	1.53	0.221	0.36
427	20.70	14.78	10.6	27.48	1.47	0.235	0.35
428	21.21	18.87	10.4	27.53	1.50	0.195	0.34
429	21.79	14.29	10.9	27.53	1.48	0.215	0.32
430	21.73	17.28	10.6	27.44	1.53	0.212	0.33

Table A.58 Wheat tissue nutrient analysis and biomass yield data from Tribune in the 2007-08 growing season.

Plot	--------------Flag Leaf--------------			---------------------Stover (Feekes 7)---------------------			
	N	P	K	N	P	K	Dry Weight
	(%)	(%)	(%)	(%)	(%)	(%)	(kg 0.35m^{-2})
121	3.89	0.321	3.19	2.67	0.260	3.47	-
122	3.83	0.321	3.19	2.51	0.189	3.13	-
123	3.89	0.297	3.10	2.37	0.195	3.06	-
124	4.14	0.365	3.61	1.93	0.136	2.75	-
125	4.09	0.326	3.48	2.41	0.219	3.45	-
126	4.06	0.341	3.47	2.11	0.166	2.81	-
127	3.98	0.368	3.35	2.18	0.189	3.20	-
128	3.79	0.334	3.32	2.25	0.173	3.07	-
129	3.97	0.342	3.42	2.34	0.195	3.43	-
130	4.06	0.370	3.54	2.68	0.223	3.59	-
211	3.86	0.288	2.79	3.39	0.298	4.30	0.625
212	3.42	0.213	2.61	3.78	0.309	4.55	0.318
213	3.55	0.203	2.50	3.46	0.298	3.94	0.38
214	3.29	0.185	2.46	3.15	0.265	3.47	0.267
215	3.41	0.200	2.32	2.16	0.188	2.72	0.577
216	3.49	0.200	2.29	1.94	0.175	2.52	0.472
217	3.24	0.198	2.18	2.71	0.218	3.78	0.553
218	3.16	0.170	2.14	2.45	0.180	3.13	0.443
219	3.42	0.224	2.37	2.36	0.203	2.83	0.306
220	3.51	0.203	2.50	2.47	0.211	4.47	0.294
301	4.14	0.294	3.28	3.20	0.292	4.51	0.099
302	3.82	0.247	2.79	2.22	0.194	2.83	0.034
303	3.54	0.189	2.39	2.71	0.257	3.77	0.024
304	3.47	0.225	2.81	2.19	0.210	2.59	0.06
305	3.68	0.234	2.23	2.71	0.235	4.11	0.141
306	3.45	0.207	2.51	2.31	0.214	2.74	0.366
307	3.60	0.210	2.62	3.01	0.236	3.98	0.218
308	3.51	0.189	2.51	2.52	0.226	3.17	0.189
309	3.55	0.213	2.57	3.06	0.276	3.38	0.257
310	3.47	0.199	2.35	3.30	0.280	3.37	0.434
401	3.66	0.239	2.51	2.67	0.260	3.47	0.073
402	3.68	0.247	2.35	2.51	0.189	3.13	0.103
403	3.61	0.244	2.60	2.37	0.195	3.06	0.131
404	3.77	0.246	2.57	1.93	0.136	2.75	0.289
405	3.69	0.241	2.59	2.41	0.219	3.45	0.126

406	3.88	0.248	2.57	2.11	0.166	2.81	0.339
407	3.67	0.244	2.45	2.18	0.189	3.20	0.097
408	3.83	0.239	2.52	2.25	0.173	3.07	0.198
409	4.02	0.246	2.52	2.34	0.195	3.43	0.057
410	3.93	0.293	2.94	2.68	0.223	3.59	0.048

Table A.59 Wheat grain yield and nutrient analysis data from Tribune in the 2007-08 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
121	23.5	6.2	17.8	53.2	0.402
122	23.3	5.3	18.9	52.2	0.402
123	22.7	6.2	13.8	56.4	0.376
124	22.6	5.8	13.9	56.2	0.424
125	22.6	6.0	13.6	56.4	0.404
126	22.4	6.2	15.9	55.4	0.385
127	22.4	7.3	14.2	56.8	0.404
128	22.3	6.9	17.3	54.3	0.417
129	22.3	7.2	18.4	52.7	0.423
130	22.3	7.1	17.2	54.7	0.422
211	30.4	15.3	12.1	57.4	0.337
212	30.5	15.8	11.2	57.9	0.342
213	30.4	17.6	10.3	56.5	0.385
214	30.3	17.6	10.5	58.1	0.333
215	30.4	17.6	10.4	56	0.363
216	30.2	16.2	10.3	56.5	0.345
217	30.2	16.8	10.5	55.9	0.364
218	30.1	16.5	10.4	58.3	0.488
219	30.2	15.9	10.4	56.3	0.308
220	30.3	15.2	10.5	58.1	0.354
301	26.7	10.9	19.9	52.6	0.364
302	26.6	8.6	19.9	52.6	0.413
303	26.3	9.4	17.4	55.4	0.361
304	26.3	9.4	18.3	53.6	0.360
305	26.3	10.1	17.9	54.5	0.323
306	26.1	13.5	11.9	59.1	0.351
307	26.1	12.0	13.5	57.9	0.325
308	25.8	12.5	12.3	57.8	0.267
309	25.8	13.0	12.4	57.4	0.346
310	25.9	13.7	11.6	55.2	0.355
401	27.6	8.5	15.0	57.5	0.322
402	28.0	10.0	12.4	59.4	0.290
403	28.3	10.8	12.0	59.4	0.289
404	28.2	15.5	11.8	58.8	0.288
405	28.0	11.3	12.1	58.1	0.327
406	28.3	13.7	11.9	57.8	0.376

407	28.3	11.6	11.8	58.3	0.352
408	28.3	12.7	12.0	58.2	0.363
409	28.4	8.0	17.2	55.5	0.370
410	28.2	8.0	17.6	54.8	0.393

Table A.60 Grain sorghum grain yield and nutrient analysis data from Tribune in the 2008 growing season.

Plot	Harvest Length (m)	Harvest Weight (kg)	Moisture (%)	Test Weight (kg)	Grain P (%)
111	19.88	12.1	13.6	26.3	0.382
112	20.12	11.0	13.9	25.6	0.428
113	21.58	12.7	12.9	26.2	0.458
114	19.64	10.2	13.1	25.7	0.461
115	15.75	9.3	13.4	25.1	0.422
116	21.55	13.1	13.3	25.6	0.450
117	23.13	18.7	13.3	26.8	0.459
118	19.43	10.8	13.5	25.9	0.424
119	22.89	8.7	15.0	24.9	0.413
120	16.66	5.2	13.6	23.2	0.405
201	18.15	13.6	13.7	26.6	0.386
202	20.55	10.8	12.8	25.3	0.440
203	20.00	10.6	12.8	26.0	0.451
204	21.46	12.4	12.9	25.3	0.455
205	16.93	8.3	12.9	25.7	0.451
206	16.87	8.1	12.4	25.2	0.439
207	23.77	17.6	13.0	26.6	0.452
208	13.62	7.0	13.3	25.6	0.454
209	22.62	15.5	12.9	26.5	0.435
210	25.02	20.9	13.7	26.9	0.396
321	16.29	14.8	14.4	25.7	0.291
322	25.99	19.2	14.0	26.2	0.264
323	19.49	15.1	14.0	25.6	0.230
324	11.34	7.9	14.3	25.2	0.228
325	-	-	-	-	-
326	14.14	8.9	15.4	24.3	0.241
327	11.31	7.3	15.1	24.4	0.254
328	8.03	6.9	14.8	24.9	0.228
329	17.02	11.4	13.5	24.4	0.233
330	8.88	7.3	14.9	24.2	0.249
411	23.68	28.4	14.4	26.6	0.371
412	24.62	23.7	13.1	26.8	0.439
413	18.57	13.5	12.9	26.1	0.423
414	14.23	10.9	13.1	26.2	0.474
415	23.16	19.5	12.7	26.5	0.440
416	21.37	12.5	12.6	26.2	0.476

417	21.83	14.1	12.5	25.7	0.493
418	10.49	5.2	12.3	25.5	0.478
419	18.42	9.2	12.4	25.4	0.477
420	20.28	8.8	12.3	25.4	0.518

Table A.61 Initial soil sample data from Tribune.

Plots	Depth (m)	pH	Buffer pH	P (ppm)	K (ppm)	SO_4^{2+} (ppm)	NH_4^+ (ppm)	NO_3^- (ppm)	OM (%)	Cl^- (ppm)
101-110	0-0.08	6.4	7.0	77	872	4.5	8.8	3.5	1.5	35.0
101-110	0.08-0.15	7.1	-	29	690	4.2	5.6	3.0	1.2	3.8
101-110	0.15-0.23	7.5	-	6	616	5.7	6.0	6.9	1.1	5.0
101-110	0.23-0.31	7.8	-	11	552	5.1	5.4	9.2	1.1	6.5
101-110	0.31-0.61	8.0	-	30	470	5.0	3.5	7.3	0.9	13.8
101-110	0.61-0.91	8.1	-	22	555	5.1	4.6	4.0	0.7	8.8
121-130	0-0.08	6.8	-	76	783	4.0	4.0	1.1	1.4	2.0
121-130	0.08-0.15	7.1	-	39	695	3.8	3.6	3.2	1.1	2.1
121-130	0.15-0.23	7.5	-	8	682	5.5	4.3	5.4	1.6	4.5
121-130	0.23-0.31	7.8	-	31	655	5.7	4.2	10.3	1.9	5.5
121-130	0.31-0.61	7.9	-	40	657	4.8	6.9	12.4	1.4	6.7
121-130	0.61-0.91	8.2	-	29	748	4.0	2.4	3.0	0.7	4.0
211-220	0-0.08	7.6	-	56	831	3.5	3.3	1.6	1.6	1.4
211-220	0.08-0.15	7.9	-	12	656	3.2	3.6	1.6	1.0	1.4
211-220	0.15-0.23	8.0	-	11	542	4.5	3.9	1.8	0.9	2.6
211-220	0.23-0.31	8.1	-	13	496	5.5	2.5	2.5	0.9	2.0
211-220	0.31-0.61	8.1	-	12	535	3.6	3.0	5.0	0.6	3.0
211-220	0.61-0.91	8.4	-	10	677	3.3	3.2	1.4	1.4	3.0
221-230	0-0.08	7.6	-	56	791	3.7	5.7	2.7	1.4	2.3
221-230	0.08-0.15	8.0	-	14	672	3.3	5.3	1.6	0.9	1.7
221-230	0.15-0.23	8.1	-	11	562	4.8	3.5	3.1	0.8	2.3
221-230	0.23-0.31	8.1	-	12	500	5.0	5.2	6.0	0.7	2.8
213-230	0.31-0.61	8.0	-	11	542	3.9	2.9	4.3	0.7	5.1
221-231	0.61-0.91	8.3	-	8	733	3.8	2.9	0.9	0.5	5.0
301-310	0-0.08	6.7	-	77	832	3.7	3.3	1.4	1.7	2.4
301-310	0.08-0.15	7.1	-	39	731	3.7	2.9	2.9	1.2	1.0
301-310	0.15-0.23	7.6	-	5	713	4.6	3.0	2.7	1.1	3.4
301-310	0.23-0.31	7.7	-	12	605	5.7	4.0	6.0	1.1	3.1
301-310	0.31-0.61	7.9	-	23	508	5.6	3.3	12.5	0.9	5.7
301-310	0.61-0.91	8.1	-	14	644	4.8	3.1	8.2	0.7	4.5
311-320	0-0.08	7.9	-	50	774	3.5	9.1	2.9	1.6	2.3
311-320	0.08-0.15	8.0	-	11	662	3.8	7.2	1.8	1.1	1.6
311-320	0.15-0.23	8.0	-	12	658	4.8	5.6	3.8	1.1	1.5
311-320	0.23-0.31	8.0	-	11	495	4.8	7.1	6.5	1.0	2.3
311-320	0.31-0.61	8.1	-	9	553	3.3	3.4	6.7	0.8	2.9
311-320	0.61-0.91	8.3	-	6	735	3.6	3.7	4.1	0.6	1.7
401-413	0-0.08	6.6	-	105	807	4.5	4.0	4.0	1.7	1.9
401-410	0.08-0.15	7.1	-	65	733	4.2	3.3	3.5	1.3	2.2
401-410	0.15-0.23	7.4	-	24	665	5.2	3.9	7.4	1.2	4.6
401-410	0.23-0.31	7.4	-	9	608	5.3	4.7	11.3	1.1	7.0
401-410	0.31-0.61	7.7	-	27	529	5.9	5.0	13.8	1.0	9.4
401-410	0.61-0.91	7.9	-	41	578	5.7	3.4	9.3	0.9	6.6
421-430	0-0.08	7.3	-	96	872	4.3	7.7	4.4	1.6	2.3
421-430	0.08-0.15	7.8	-	41	676	4.1	7.2	2.8	1.1	2.1
421-430	0.15-0.23	7.7	-	5	615	5.9	3.6	5.8	0.9	3.9
421-430	0.23-0.31	7.8	-	8	555	6.6	5.8	9.6	1	7.7
421-430	0.31-0.61	8.1	-	36	547	4.6	4.2	6.1	0.8	8.1
421-430	0.61-0.91	8.2	-	30	662	4.5	3.9	1.7	0.8	1.1

Table A.62 Soil sample data from Tribune collected in 2008 from directly under the crop row and centered between crop rows at incremental depths.

Plot	Depth (m)	Location	P (ppm)
101	0-0.08	Row	55
101	0.08-0.15	Row	18
101	0.15-0.23	Row	10
101	0.23-0.31	Row	15
101	0.31-0.61	Row	22
101	0-0.08	Row Middle	57
101	0.08-0.15	Row Middle	18
101	0.15-0.23	Row Middle	8
101	0.23-0.31	Row Middle	10
101	0.31-0.61	Row Middle	18
107	0-0.08	Row	67
107	0.08-0.15	Row	20
107	0.15-0.23	Row	6
107	0.23-0.31	Row	9
107	0.31-0.61	Row	25
107	0-0.08	Row Middle	73
107	0.08-0.15	Row Middle	18
107	0.15-0.23	Row Middle	8
107	0.23-0.31	Row Middle	10
107	0.31-0.61	Row Middle	40
108	0-0.08	Row	90
108	0.08-0.15	Row	22
108	0.15-0.23	Row	14
108	0.23-0.31	Row	11
108	0.31-0.61	Row	34
108	0-0.08	Row Middle	63
108	0.08-0.15	Row Middle	17
108	0.15-0.23	Row Middle	17
108	0.23-0.31	Row Middle	12
108	0.31-0.61	Row Middle	34
110	0-0.08	Row	69
110	0.08-0.15	Row	19
110	0.15-0.23	Row	10
110	0.23-0.31	Row	11

110	0.31-0.61	Row	27
110	0-0.08	Row Middle	109
110	0.08-0.15	Row Middle	27
110	0.15-0.23	Row Middle	17
110	0.23-0.31	Row Middle	12
110	0.31-0.61	Row Middle	31
221	0-0.08	Row	51
221	0.08-0.15	Row	7
221	0.15-0.23	Row	14
221	0.23-0.31	Row	15
221	0.31-0.61	Row	15
221	0-0.08	Row Middle	58
221	0.08-0.15	Row Middle	11
221	0.15-0.23	Row Middle	10
221	0.23-0.31	Row Middle	16
221	0.31-0.61	Row Middle	16
224	0-0.08	Row	13
224	0.08-0.15	Row	54
224	0.15-0.23	Row	11
224	0.23-0.31	Row	14
224	0.31-0.61	Row	15
224	0-0.08	Row Middle	48
224	0.08-0.15	Row Middle	13
224	0.15-0.23	Row Middle	11
224	0.23-0.31	Row Middle	14
224	0.31-0.61	Row Middle	20
226	0-0.08	Row	74
226	0.08-0.15	Row	13
226	0.15-0.23	Row	12
226	0.23-0.31	Row	13
226	0.31-0.61	Row	16
226	0-0.08	Row Middle	62
226	0.08-0.15	Row Middle	12
226	0.15-0.23	Row Middle	13
226	0.23-0.31	Row Middle	15
226	0.31-0.61	Row Middle	17
230	0-0.08	Row	31

230	0.08-0.15	Row	10
230	0.15-0.23	Row	13
230	0.23-0.31	Row	14
230	0.31-0.61	Row	15
230	0-0.08	Row Middle	47
230	0.08-0.15	Row Middle	8
230	0.15-0.23	Row Middle	13
230	0.23-0.31	Row Middle	15
230	0.31-0.61	Row Middle	13
313	0-0.08	Row	68
313	0.08-0.15	Row	15
313	0.15-0.23	Row	13
313	0.23-0.31	Row	14
313	0.31-0.61	Row	19
313	0-0.08	Row Middle	54
313	0.08-0.15	Row Middle	12
313	0.15-0.23	Row Middle	11
313	0.23-0.31	Row Middle	13
313	0.31-0.61	Row Middle	15
314	0-0.08	Row	49
314	0.08-0.15	Row	14
314	0.15-0.23	Row	13
314	0.23-0.31	Row	14
314	0.31-0.61	Row	13
314	0-0.08	Row Middle	41
314	0.08-0.15	Row Middle	10
314	0.15-0.23	Row Middle	12
314	0.23-0.31	Row Middle	12
314	0.31-0.61	Row Middle	15
317	0-0.08	Row	24
317	0.08-0.15	Row	10
317	0.15-0.23	Row	10
317	0.23-0.31	Row	11
317	0.31-0.61	Row	11
317	0-0.08	Row Middle	33
317	0.08-0.15	Row Middle	10
317	0.15-0.23	Row Middle	10

317	0.23-0.31	Row Middle	10
317	0.31-0.61	Row Middle	9
319	0-0.08	Row	32
319	0.08-0.15	Row	10
319	0.15-0.23	Row	11
319	0.23-0.31	Row	11
319	0.31-0.61	Row	12
319	0-0.08	Row Middle	49
319	0.08-0.15	Row Middle	10
319	0.15-0.23	Row Middle	10
319	0.23-0.31	Row Middle	10
319	0.31-0.61	Row Middle	11
421	0-0.08	Row	101
421	0.08-0.15	Row	38
421	0.15-0.23	Row	8
421	0.23-0.31	Row	14
421	0.31-0.61	Row	32
421	0-0.08	Row Middle	91
421	0.08-0.15	Row Middle	34
421	0.15-0.23	Row Middle	5
421	0.23-0.31	Row Middle	13
421	0.31-0.61	Row Middle	37
424	0-0.08	Row	108
424	0.08-0.15	Row	26
424	0.15-0.23	Row	7
424	0.23-0.31	Row	12
424	0.31-0.61	Row	33
424	0-0.08	Row Middle	72
424	0.08-0.15	Row Middle	18
424	0.15-0.23	Row Middle	6
424	0.23-0.31	Row Middle	9
424	0.31-0.61	Row Middle	29
426	0-0.08	Row	55
426	0.08-0.15	Row	13
426	0.15-0.23	Row	8
426	0.23-0.31	Row	12
426	0.31-0.61	Row	26

426	0-0.08	Row Middle	51
426	0.08-0.15	Row Middle	16
426	0.15-0.23	Row Middle	5
426	0.23-0.31	Row Middle	9
426	0.31-0.61	Row Middle	25
428	0-0.08	Row	108
428	0.08-0.15	Row	18
428	0.15-0.23	Row	8
428	0.23-0.31	Row	14
428	0.31-0.61	Row	28
428	0-0.08	Row Middle	66
428	0.08-0.15	Row Middle	20
428	0.15-0.23	Row Middle	7
428	0.23-0.31	Row Middle	8
428	0.31-0.61	Row Middle	36

Additional Observations

Table A.63 Relative sorghum head emergence at Manhattan in 2008.

Treatment	Relative Head Emergence (%)
1	28
2	100
3	72
4	77
5	85
6	87
7	41
8	90
9	100
10	100
11	74
12	87

Relative head emergence was calculated by counting the number of heads exposed from the leaf sheath for each plot and setting the treatment with the highest emergence at 100%.

Table A.64 Relative corn tassel emergence at Scandia in 2008.

Treatment	Relative tassel Emergence (%)
1	0
2	2
3	2
4	1
5	63
6	66
7	100
8	1
9	0
10	84
11	10
12	71

Relative tassel emergence was calculated by counting the number of tassels exposed from the leaf sheath for each plot and setting the treatment with the highest emergence at 100%.